ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

DETERMINATION OF THE BEHAVIOUR OF A SUBMERGED MEMBRANE BIOREACTOR OPERATED AT LOW SLUDGE RETENTION TIME

M.Sc. THESIS

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<u>**İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ**</u>

DÜŞÜK ÇAMUR YAŞINDA İŞLETİLEN BATIK MEMBRAN BİYOREAKTÖRDE ARITMA PERFORMANSININ İNCELENMESİ

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Date of Submission : 31 August 2012
Date of Defense : 17 September 2012

FOREWORD

First of all I would like to thank my supervisor Prof. Dr. Seval SÖZEN, my thesis advisor who provided me the opportunity to work for the distinguished research project supported by the Scientific and Technical Research Council of Turkey (TUBITAK) and for her valuable guidance.

I would like to express my great appreciation to Prof. Dr. Derin ORHON for his scientific guidance and valuable discussions. I would also like to thank to Prof. Dr. Emine UBAY ÇOKGÖR for the evaluation of my respirometric tests and for her valuable discussions.

I would like to acknowledge TUBITAK (Project No: 109Y261) for financially supporting the research described in this thesis.

I would like to express my great appreciation to MSc Senem TEKSOY BAŞARAN for her understanding and positive energy. She was continually supportive and encouraging me at the times when I most needed.

On top of it all, I would like to thank my mother, Nuran AYSEL for all her love, support and patience on my endless complains. I also would like to thank my brother Sefa AYSEL who always gave me the reason to smile.

Finally, I want to thank Mustafa for his support and patience during my graduate studies.

September 2012 Merve AYSEL
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ABBREVIATIONS

BOD : Biological Oxygen Demand
COD : Chemical Oxygen Demand
ÇMÜ : Çözünmüş Mikrobiyal Ürün
ÇY : Çamur Yaşı
DOC : Dissolved Organic Carbon
EPS : Extra Polymeric Substances
F/M : Food to Microorganism ratio
HRT : Hydraulic Retention Time
KES : Kapiler Emme Süresi
MBR : Membrane Bioreactor
MF : Microfiltration
MLSS : Mixed Liquor Suspended Solids
MLVSS : Mixed Liquor Volatile Suspended Solids
MW : Molecular Weight
OLR : Organic Loading Rate
PHA : Poly hydroxyl alkanoate
PHB : Poly-b-hydroxybutyrate
PHV : Poly hydroxyvalerate
PLC : Programmable Logic Controller
SMBR : Submerged Membrane Bioreactor
SMP : Soluble Microbial Products
SRT : Sludge Retention Time
SS : Suspended Solids
TMP : Trans Membrane Pressure
TOC : Total Organic Carbon
UF : Ultrafiltration
VSS : Volatile Suspended Solids

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DETERMINATION OF THE BEHAVIOUR OF A SUBMERGED MEMBRANE BIOREACTOR OPERATED AT LOW SLUDGE RETENTION TIME

SUMMARY

Membrane Bioreactor (MBR) technology is a wastewater treatment technology combining the biological treatment in the activated sludge process with membrane filtration. MBR system replaces the clarification tanks used in conventional activated sludge systems since the biomass separation is done by the membrane filtration. Effluents with high quality are obtained through retention of biomass and suspended solids by the membrane. MBR systems offer several operational advantages. Enforcement of municipal and industrial wastewater discharge standards and increasing number of recycle/reuse applications have resulted in preference of MBR system applications.

The general approach in MBR applications is to operate these systems at longer sludge retention times (SRT) in order to have higher biomass concentrations in the bioreactor, to allow slowly-growing microorganism to grow in the system and to reduce the volume of sludge to be handled. Although the reduced amount of biomass production obtained at higher SRT may seem advantageous in terms of system operation and sludge handling, the new approaches in energy, especially the policies targeting self-sufficient treatment plants, are stating that the biomass is actually a valuable alternative fuel in terms of energy production.

The purpose of this study is to investigate the performance of submerged MBR system operated at extremely low SRT in removing readily biodegradable/soluble COD from wastewater. In this respect, a laboratory scale submerged MBR was operated at three different SRT of 2.0, 1.0 and 0.5 days. For each level of the selected sludge age, hydraulic retention time (HRT) of the system was adjusted to 8 hours. Two different synthetic substrate feedings were tested; (a) soluble/readily biodegradable substrate mixture and (b) acetate. The synthetic mixture representing readily biodegradable COD in wastewater was tested at all SRTs, whereas synthetic feed constituting only acetate was tested only at SRT of 1.0 day. The synthetic feeds were adjusted to first 200 mg COD/L and than 1000 mg COD/L for the experimental runs.

The experimental works covered (i) determination of the process performance sustained at steady-state, (ii) respirometric tests, (iii) evaluation of the substrate storage, (iv) evaluation of sludge dewaterability.

Operation of the submerged MBR at selected operational conditions have shown that, high quality effluents could be achieved even at very low SRT, i.e. SRT = 0.5 – 2.0 days, where the COD removal performance was above 90 % under all conditions. In the case where synthetic substrate mixture representing the readily biodegradable soluble portion of the wastewater was used having 200 mg COD/L and 1000 mg

COD/L; the effluent COD remained below 18 mg COD/L and 56 mg COD/L, respectively. Likewise for the synthetic substrate only constituting acetate having 200 mg COD/L and 1000 mg COD/L; the effluent COD remained below 20 mg COD/L and 29 mg COD/L, respectively. The soluble COD profiles monitored inside the bioreactors tended to be higher than the COD values observed in the effluent streams which was attributed to generation of SMPs during the biological processes as the influent COD was assumed to be totally biodegradable, which was supported with the finding that the SMP increased with the increasing SRT. The levels of proteins and carbohydrates were also measured in the reactor bulk liquid. The levels of these compounds, which are commonly associated with SMPs, were measured in the range of 2.59 – 9.62 mg COD/L, which constitute only a small fraction of the residual COD entrapped in the MBR. .

The study also covered respirometric tests, which were implemented for the synthetic substrate mixture representing readily soluble COD in wastewater at SRT of 2.0, 1.0 and 0.5 d; and for synthetic substrate constituting only acetate with 200 mg/L and 1000 mg/L COD concentration, at SRT of only 1.0 d. In the respirometric studies run with synthetic substrate mixture, for both feeds adjusted to 200 mg COD/L and 1000 mg COD/L. It was observed that the time required to reduce the soluble COD in the batch reactor to its level at the endogeneous phase was decreased as the SRT was decreased. This was attributed to the dominance of active biomass in the case of operation at low SRT, compared to the relatively inactive biomass observed in reactors when long SRTs are employed. In the respirometric studies run with acetate, for both feeds adjusted to 200 mg COD/L and 1000 mg COD/L, it was again observed that all the COD introduced beginning of the test was reduced to its endogenous phase.

Storage polymers were investigated in the samples taken from parallel batch tests, where the synthetic feeds were adjusted to 1000 mg COD/L. Analysis of storage polymers, namely, poly hydroxyl alkanoate (PHA), poly-b-hydroxybutyrate (PHB) and poly hydroxyvalerate (PHV) have shown significant difference between the two synthetic feeds. For the synthetic feed constituting only acetate, the results indicated that there was no PHV storage and the levels of PHA and PHB storage were almost equal. In the case where the readily biodegradable substrate mixture was tested, all three polymers could be detected. The results were consistent with the literature findings.

In order to support the potential use of sludge generated in the suggested MBR operation approach, as an alternative fuel and to have data on its fouling propensity, it is important to determine the dewaterability of the sludge. The sludge samples obtained from all experimental runs were analyzed for their Capillary Suction Time (CST) values. The CST analysis indicated that, for both synthetic substrates tested, when the SRT was increased, the sludge dewaterability properties deteriorated. These experimental results were compatible with the protein and carbohydrate measurements, which also indicated that protein and carbohydrate concentrations associated with the fouling species, EPS and SMP, increased with increasing SRT.

DÜŞÜK ÇAMUR YASINDA İŞLETİLEN BATIK MEMBRAN BİYOREAKTÖRDE ARITMA PERFORMANSININ İNCELENMESİ

ÖZET

Membran Biyoreaktör (MBR) teknolojisi, aktif çamur prosesi ile elde edilen biyolojik arıtımın ve membran filtrasyonunun bir arada kullanıldığı bir atıksu arıtma teknolojisidir. Sistemde oluşan biyokütlenin atıksudan ayrımı membran filtrasyonu ile sağlandığından konvansiyonel aktif çamur arıtma sistemlerindeki çöktürme işlemine gerek kalmamaktadır. Membran biyorekatör sistemleri ile biyokütle ve askıda katı maddenin membran vasıtasıyla tutulması sağlanarak yüksek kalitede çıkış suyu elde edilmektedir. Günümüzde evsel ve endüstriyel atıksu arıtımında deşarj standartlarının daha sıkı uygulanması, su kaynaklarının giderek azalması, suya olan ihtiyacın artması dolayısıyla geri kazanıma yönelik uygulamaların artması MBR uygulamalarının tercih edilmesine neden olmaktadır.

MBR uygulamalarında genel yaklaşım, oluşan biyokütlenin sistemden uzaklaştırma problemi olmadığından reaktörde yüksek biyokütle konsantrasyonu sağlayacak, çoğalma hızları düşük (yavaş çoğalan) mikroorganizmaların sistemde çoğalmasına izin verecek ve atılan çamur miktarını azaltacak şekilde uzun çamur yaşlarında (ÇY) işletilmesidir. Fakat bu yaklaşım ile konvansiyonel aktif çamur arıtma sistemlerinde hali hazırda yürütülmekte olan uygulamalar devam ettirilmiş, MBR sistemleri yenilikçi bir arıtma yaklaşımı geliştirilmesinde kullanılamamıştır. Bu çalışmada sunulan işletme yaklaşımı ile MBR teknolojisinin atıksu arıtımında yenilikçi bir uygulama olarak performansı incelenerek, konvansiyonel atıksu arıtma yaklaşımına farklı ve çevresel açıdan daha gelişmiş ve ekonomik bir alternatif sunulmuştur.

Konvansiyonel atıksu arıtma tesislerinde yüksek çamur yaşı uygulanarak elde edilen düşük biyokütle üretimi, her ne kadar işletme ve çamur bertarafı açısından avantajlı görünmekle birlikte yeni yaklaşımlar ve özellikle enerji açısından kendi kendine yetebilen arıtma tesislerine yönelik hedefler göz önüne alındığında, biyokütlenin aslında enerji üretimi açısından kıymetli bir alternatif yakıt olarak kullanılması gerektiğini ortaya koymaktadır.

Bu çalışmanın amacı, düşük çamur yaşında işletilen batık membran konfigürasyonlu bir MBR sistemi (bMBR) ile atıksuda hızlı ayrışabilen/çözünmüş halde bulunan organik maddenin giderim performansının incelenmesidir. Bu bağlamda laboratuar ölçekli bMBR sistemi, 2 gün, 1 gün ve 0.5 gün olmak üzere üç farklı çamur yaşında ve hidrolik bekletme suresi (HBS) 8 saat olacak şekilde iki farklı substrat çeşidi ile işletilmiştir. Deneysel çalışmalarda (a) atıksulardaki çözünmüş/ hızlı ayrışabilen substratı temsil eden karışım çözeltisi ve (b) yalnızca asetatın substrat olarak kullanıldığı çözelti olmak üzere iki farklı sentetik besleme kompozisyonu kullanılmıştır.

Deneysel çalışmalarda atıksudaki hızlı ayrışabilen/çözünmüş organik maddeyi temsil eden substrat karışımı ile 2 gün, 1 gün ve 0.5 gün çamur yaşlarında, asetat ile ise sadece 1 gün çamur yaşında 200 mg KOİ/L ve 1000 mg KOİ/L konsantrasyonlarında çalışılmıştır. Elde edilen bulgular; (i) kararlı halde sistem performansı (ii) respirometrik testler (iii) substrat depolama ürünleri ve (iv) çamur susuzlaştırma özelliklerinin belirlenmesi doğrultusunda değerlendirilmiştir.

Seçilen koşullarda isletilen bMBR sistemi ile elde edilen sonuçlar; öncelikle düşük çamur yaşlarında (0.5 – 2.0 gün) oldukça yüksek kalitede çıkış suyu elde edilebileceğini ve tüm işletme koşullarında KOİ giderim veriminin % 90'nın üzerinde olduğunu göstermiştir. Atıksuda hızlı ayrışabilen/çözünmüşKOİ'yi temsil eden sentetik substrat karışımı ile sırasıyla 200 mg KOİ/L ve 1000 mg KOİ/L giriş besleme konsantrasyonları yürütülen deneysel çalışmalarda, membran çıkış suyunda KOİ konsantrasyonlarının 18 mg/L ile 56 mg/L arasında olduğu gözlenmiştir. Aynı şekilde yalnızca asetattan oluşan substrat ile sırasıyla 200 mg KOİ/L ve 1000 mg KOİ/L giriş besleme konsantrasyonları ile yürütülen çalışmada membran çıkış suyunda KOİ konsantrasyonlarının 20 mg/L ile 29 mg/L arasında olduğu gözlenmiştir.

Deneysel çalışma süresince reaktör içi KOİ konsantrasyonunun membran çıkış suyunda ölçülen KOİ konsantrasyonundan yüksek olduğu gözlemlenmiş ve sisteme beslenen substrat bileşiminin de biyolojik olarak tamamıyla parçalanabilir olduğu dikkate alınarak, bu durumun sistem içerisinde gerçekleşen biyolojik faaliyetler sonucunda oluşan kalıcı çözünmüş mikrobiyal ürünlerin (ÇMÜ) neden olduğu ileri sürülmüştür. Reaktör içinde tespit edilen ÇMÜ konsantrasyonlarının, artan çamur yaşı ile birlikte artış göstermesi bu sonucu destekler niteliktedir. Bu ölçümlere ilave olarak reaktör içerisindeki çamurda ÇMÜ ile ilişkili olduğu bilinen protein ve karbonhidrat analizleri yapilmis ve ölçülen protein ve karbonhidrat konsantrasyonlarının 2.59 – 9.62 mg KOİ/L arasında değiştiği gözlenmiştir.

Bu çalışma kapsamında ayrıca, uygulanan çamur yaşı ve test edilen substratlar özelinde mikrobiyal davranışın ve giderim kinetiklerinin gözlemlenmesi amacıyla respirometrik ölçümler yürütülmüştür.

Respirometrik ölçümler, giriş besleme konsantrasyonları 200 mg KOİ/L ve 1000 mg KOİ/L olacak şekilde, kolay ayrışan çözünmüş organik maddeyi temsil eden sentetik atıksu çözeltisi ile beslenen, 2 gün, 1 gün ve 0.5 gün çamur yaşı ile işletilen ve sadece asetat içeren sentetik atıksu çözeltisi ile beslenen ve 1 gün çamur yaşı uygulanan setlerde yürütülmüştür. Kolay ayrışan çözünmüş organik maddeyi temsil eden sentetik atıksu çözeltisi beslenerek yürütülen setlerde, başlangıçta sisteme verilen organik maddenin tamamının tüketildiği ve respirometrik ölçümlerin içsel solunum fazı seviyesine düştüğü gözlenmiştir. Bu durum respirometrik ölçümlere paralel olarak yürütülen KOI giderimi ölçümleri ile de desteklenmiştir. ÇY'nın azalması ile birlikte respirometrik ölçümlerde organik madde gideriminin daha kısa sürede gerçekleştiği gözlemlenmiştir. Bu da nispeten daha düşük çamur yaşlarında aktif biyokütlenin karışım içinde daha fazla olduğunun bir göstergesidir. Benzer sonuçlara asetat beslenen deneylerde de ulaşılmıştır.

Yürütülen deneysel çalışmada batık MBR sisteminin her iki sentetik atıksu çözeltisi ile (hızlı ayrışabilen/çözünmüş organik maddeyi temsil eden substrat karışımı ve asetat) 1000 mg/L KOİ konsantrasyonuna sahip olacak şekilde beslenerek yürütülen setlerin respirometrik testleri sırasında, çamurdan alınan örnekler üzerinde depolama ürünlerinin analizi yapılmıştır. Elde edilen deneysel veriler sonucunda poly hydroxyl alkanoate (PHA), poly-b-hydroxybutyrate (PHB) ve poly hydroxyvalerate (PHV) depolama miktarları arasında substrat çeşidine ve bileşimine bağlı olarak büyük farklar olduğu görülmüştür. Yalnızca asetatın substrat olarak beslendiği sistemde oluşan çamur numunesinde yapılan depolama ürünleri analizi sonucunda PHV depolama ürününe rastlanmamış, bununla birlikte eşit miktarda PHA ve PHB tespit edilmiştir. Kolay ayrışan çözünmüş KOİ'yi temsil eden substrat karışımının beslendiği sistemde oluşan çamur numunesinde yapılan depolama ürünleri analizi sonucunda ise, PHV, PHA ve PHB olacak şekilde, üç depolama ürünü de tespit edilmiştir.

Çalışmada ileri sürülen MBR işletim yaklaşımı ile, sistemde oluşan çamurun alternatif bir yakıt olarak kullanılabilirliğini desteklemek ve membran tıkanma potansiyeli ile ilgili veri elde etmek üzere, çamur susuzlaştırma özellikleri Kapiler Emme Süresi (KES) parametresi üzerinden incelenmiştir.

Tüm deney setlerinde biyokütle üzerinde KES tayini yapılmış, her iki sentetik atıksu çözeltisi için (hızlı ayrışabilen/çözünmüş organik maddeyi temsil eden substrat karışımı ve asetat), ÇY artması ile birlikte KES'nin arttığı, yani çamur susuzlaştırma özelliğinin kötüleştiği görülmüştür. Elde edilen bulgular, aynı koşullarda ölçülen protein ve karbonhidrat seviyeleri ile birlikte değerlendirildiğinde çözünmüş mikrobiyal ürünler ile ilişkili olduğu bilinen çözünmüş protein ve karbonhidrat değerlerinin artan çamur yaşı ile yükseldiğini göstermektedir.

1. INTRODUCTION

1.1 Relevance of the Subject

During the last three decades, numerous research studies have been conducted in the field of biological wastewater treatment regarding the characteristics, biodegradabilities and treatabilities of wastewaters and the results of these studies have been exploited in understanding of wastewater characterization. Experimental results obtained from these studies have not been reflected in the application field and the wastewater treatment systems have been restricted to the application of conventional biological wastewater treatment systems that consist of pre-settling, the activated sludge system and sludge stabilization. The recent approaches that direct environmental protection such as the *sustainable environmental management* and *material and energy recyle* are actually urging now for new treatment technologies and/or technology applications.

1.2 Aim and Scope of the Study

The purpose of this study is to investigate the performance of a submerged membrane biorector (sMBR) system operated at extremely low SRT in removing readily biodegradable/soluble COD from wastewater. In this respect, a laboratory scale submerged MBR was established and operated at three different SRT of 2.0, 1.0 and 0.5 days. For each level of the selected sludge age, hydraulic retention time (HRT) of the system was adjusted to 8 hours. Two different synthetic substrate feedings were tested; (a) soluble/readily biodegradable substrate mixture and (b) acetate. The synthetic mixture representing readily biodegradable COD in wastewater was tested at all SRTs, whereas synthetic feed constituting only acetate was tested only at SRT of 1.0 day. The synthetic feeds were adjusted to first 200 mg COD/L and than 1000 mg COD/L for the experimental runs.

2. LITERATURE REVIEW

2.1 Membrane Bioreactor Technology

MBR system is the combination of biological wastewater treatment processes and membrane filtration unit where the membrane filtration is used to provide separation of the treated wastewater from the biomass (Chang, 2011). MBRs have been used for treatment of both municipal and industrial wastewater (Brindle and Stephenson, 1996; Trussell et all., 2000) and for reuse applications. MBR technology has undergone rapid development in last decade and is becoming a popular treatment option as a result of its growing confidence and flexibility.

The performance of MBR systems have been investigated in laboratory and pilot scale systems, tested with various sythetic and real wastewaters with different degradabilites (Al-Halbouni et al., 2008; Pollice et al., 2008; Ahmed et al, 2007; Jinsong et al., 2006) and industrial wastewaters (Artiga et al., 2005; Dhaouadi & Marrot, 2008).

To provide a better understanding of membrane technology, membrane fouling and its mechanism has been investigated in most of the studies in the literaure, which result in decreased efficiency, limited membrane lifespan and increased operational costs. (Judd, 2004; P. Le-Clech et al.,2006; Amy, 2008; Jiang et al., 2012).

The MBR applications can be realized with different membrane types and configurations. Membrane materials can be polymeric or organic (polyetylene, polyethersulfane, polysulfane, etc.) as well as of metallic (Titanium dioxide, Zirkonium dioxide), glass and ceramic types. The membrane configurations can be hollow fibre, tubular and/or flat sheet types (Cicek, 2003). Flat-sheet or hollow fiber configurations are preferred in submerged MBR systems whereas tubular configuration is preferred in external MBR systems (Judd, 2007).

Research on MBR technology began over 40 years ago, the first reported application of MBR technology was in 1969 and since this time very generations MBR systems have evolved (A.N.L. Ng, A.S. Kim, 2007; W. Yang et al., 2006).

Until the beginning of 2000, MBR systems have mostly been used to treat domestic wastewater, industrial wastewater and other characteristic wastewaters, where a small footprint, water reuse were required (Yang et al., 2006). Today it is clear that MBR systems has developed rapidly and gained attention.

2.1.1 Configuration of MBRs

MBRs can be classified basically into two groups: The side-steam MBR and submerged MBR. The first configuration is a submerged configuration with the membrane module immersed in the activated sludge (Figure 2.1). The second is a recirculated configuration with an external membrane unit (Figure 2.2) where mixed liquor is pumped to the outside of the reactor to the membrane module, the pressure drives the separation of water from the sludge. The concentrated and particular fraction of sludge is then recycled back into the reactor.

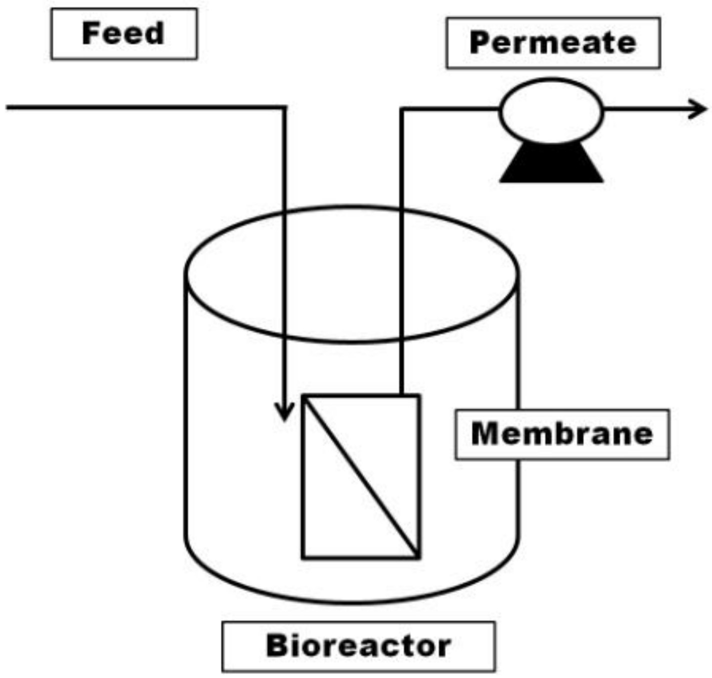

Figure 2.1 : Configuration of submerged MBR.

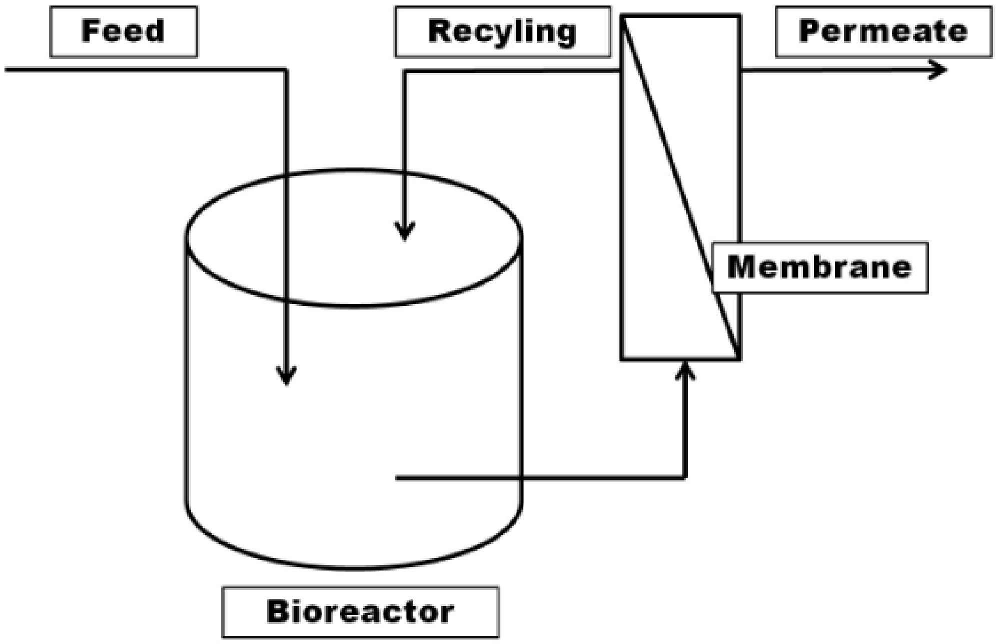

Figure 2.2 : Configuration of side-stream MBR.

The operating characteristics that belong to side-stream and submerged MBRs are summarized in Table 2.1. The submerged MBR has a basic configuration. It requires a suction pump and an aerator. Aeration of the bioreactor not only satisfies the oxygen need for the biological treatment, but it also helps to control membrane fouling in submerged MBRs. One of the biggest and known advantage of submerged MBRs is energy saving by using aeration and lower fluxes (10-30 $L/m^2.h$) as opposed to the external MBRs recirculation pump costs and high fluxes (40-100 $L/m^2.h$).

Table 2.1 : The comparison of side-stream MBRs and submerged MBRs.

Submerged Membranes	**External Membrane System with high recycling rate**
Aeration cost high (- 90%)	Aeration cost low (- 20%)
Very low pumping costs	High pumping costs
Lower flux (larger footprint)	Higher flux (smaller footprint)
Less frequent cleaning required	More frequent cleaning required
Lower operating costs	Higher operating costs
Higher capital costs	Lower capital costs

2.1.2 Advantage and disadvantage of MBRs

MBRs have advantages and disadvantages when compared with conventional activated sludge systems (CAS). Membrane technology is known with its ability of good separation of treated water from sludge. In conventional activated sludge systems the most common problem is sludge bulking because of the floc structures formed in these systems. In the MBR systems, the biomass separation system can easily eliminate sludge bulking problems. Another advantage is the independence of selecting operating parameters , which resulted in increased popularity of MBRs. MBRs provide wide range selection of HRT and SRT. Advantages of MBRs compared to CAS can be summarized as follows:

- Production of reusable water cause of high quality effluent
- Sludge bulking control the ability of separation
- Small footprint
- High loading rate and shorter hydraulic retention times
- Longer SRTs resulting less sludge production
- Treatment area minimization
- Rapid start-up of biological processes

On the other hand MBR has several disadvantages and these are can be summarized as follows:

- The complexity of control system
- Fouling problems
- High operating costs (X.-y. Li, X.-m. Wang., 2006; T. Buer, J. Cumin., 2010; Chang., 2011).

2.2 Filtration Process in MBRs

2.2.1 Overview of membrane filtration process

In membrane operations the filtration principle depends on separation of a mixture of substances with a selective thin film (Jiang, PhD). The degree of selectivity depends on the membrane pore size (Judd, 2007). The optimized membrane pore size should not be too big to cause membrane blocking (Lee et al., 2004) and it should not be too small to reduce membrane permeability (Stephenson et al., 2000).

In MBR systems, mostly microfiltration (MF) or ultrafiltration (UF) membrane modules are used. Microfiltration (MF) and ultrafiltration (UF) processes achieve a separation by physical elimination. MF is capable of removing suspended solids to about 0.05μm in size and UF is able to remove colloidal and dissolved species. In addition to these; nanofiltration (NF) and reverse osmosis (RO) are also applied in filtration processes. Types of membranes and their filtration range can be seen in Figure 2.2.

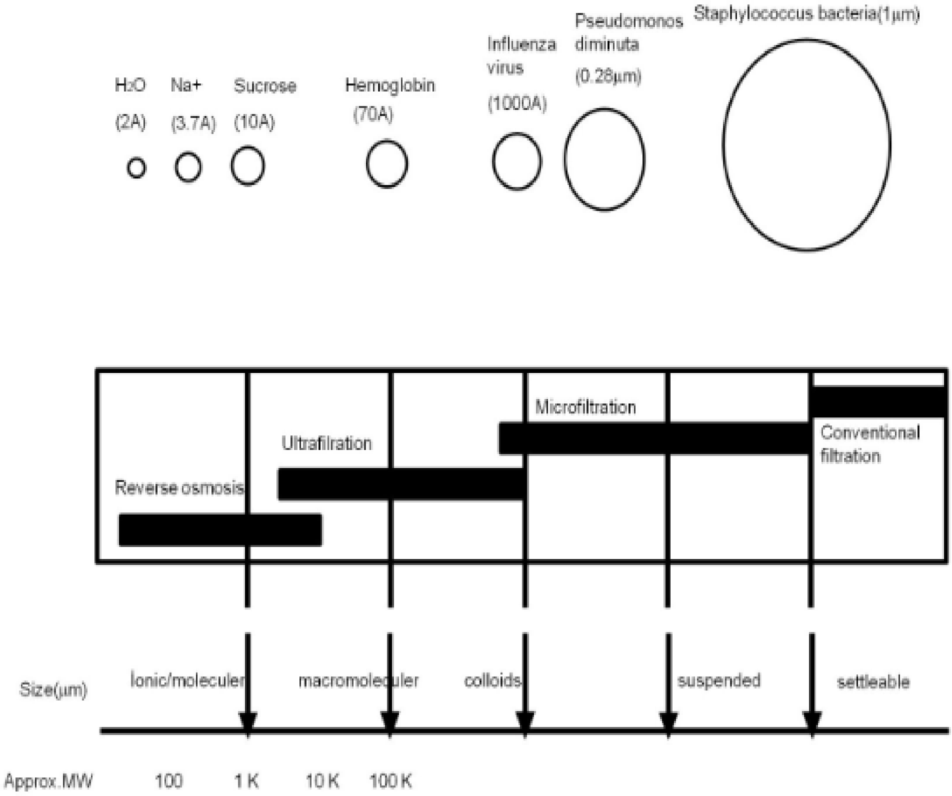

Figure 2.3 : Classification of membrane processes (adopted from Richard., 2004).

2.2.2 Membrane fouling

Membrane fouling is a still major problem in most MBR applications despite of its advantages over to CAS. Therefore, most of the MBR studies aim to investigate causes, characteristics and mechanisms of fouling The fouling mechanism is affected by many factors such as membrane configuration, wastewater characteristics and operating which can be grouped as biomass related aspects and operation conditions (Judd, 2004). The factors affecting fouling and controlling approaches can be seen in Figure 2.4 (modified from Meng et al., 2009).

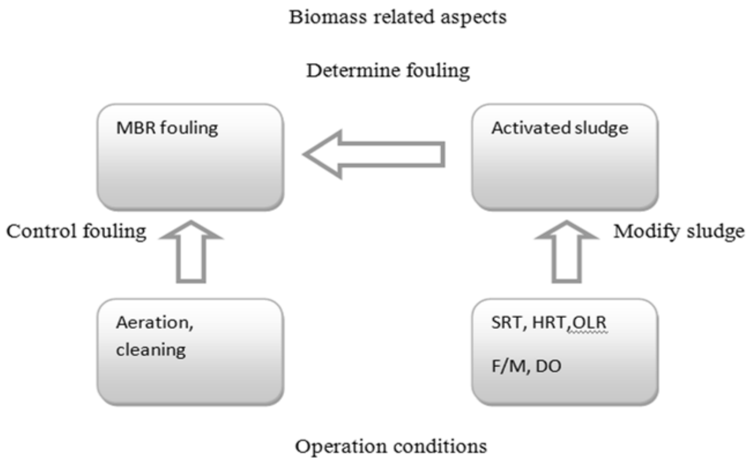

Figure 2.4 : Fouling mechanism in MBR.

As depicted in the Figure 2.4 and from many studies, operation conditions such as SRT, HRT, organic loading rate (OLR), food to microorganism ratio (F/M) and dissolved oxygen (DO) are important parameters to understand the membrane fouling complexity and MBR performance.

2.3 MBR Performance

2.3.1 Effect of sludge age on MBR performance

SRT is an important parameter that attracted the attention in most MBR studies and which is correlated with the membrane fouling.

In several recent studies different aspects of SRT were examined; some researchers focused on lab-scale plants (Song et al., 2007), full-scale (Hollender et al., 2007), others analysed extremely low to extremely high SRT (Masse´ et al., 2006; H.Y. Ng, S.W. Hermanowicz, 2005).

SRT has been widely acknowledged to be an important factor influencing membrane fouling (Broeck et al., 2012). In many studies, it was found that soluble organic matter, particulate size distribution, volatile/suspended solid (MLSS/MLVSS), sludge viscosity, bound EPS and SMP are changing with different with SRTs (Le Clech et al., 2006; Ahmed et al., 2007; G. Laera et al.,2009).

Many studies focused on the effluent quality and membrane fouling resulting from operation of MBR systems at different SRT (Ahed et al., 2007; Al-Halbouni et al., 2008; Ng et al., 2005; G. Laera et al., 2009; Broeck et al., 2012).

Many studies in literature have shown contradictory results on the effect of SRT on MBR performance. In the study performed by Trussell et al.(2006), it was found that when SRT was decreased to 5 days from 10 days, membrane fouling increased. Another study performed by Han et al (2005) found that increasing the SRT from 30 to 100 days, increased membrane fouling.

In MBR systems, higher SRTs are preferred, as employing high SRT allows biodegradation of specific organic pollutants by slow growing microorganisms, operating at higher MLSS concentrations which reduces the amount of sludge to be wasted hence reduces the footprint of sludge handling (Broeck et al., 2012). Many studies have reported that MBRs show good performance with SRT longer than 10 days.

Pollice et al. (2008); reported good COD removal over to 85 % and complete nitrification with a lab-scale submerged MBR operated at SRT of 20 days and no sludge wastage. Jinsong et al. (2006) reported 93 to 97 % TOC removal with a submerged MBR system having a flat-frame microfiltration module, which was operated at SRT of 10 days and 30 days. Ahmed et al. (2007) found that the COD removal efficiency is 98 % and higher for four sequential anoxic/anaerobic MBR operated at SRT between 20 days and 100 days. Tan et al. (2008) reported perfect COD removal efficiencies (over 95 %) who investigated the effect of SRT on treatment of municipal wastewater with 4 bench-scale pre-denitrification submerged MBR syetems operated at SRT: 5, 8.3, 16.7, and 33.3 days.

After the investigation of long SRTs successful effect in organic matter removal efficiencies in MBRs, the fouling problem which is relevant with different SRTs has gained attention. G. Laera et al., 2009; Broeck et al., 2012; W. Chen et al., 2012 have investigated the effect of SRT on membrane fouling, cleaning and operation.

On the other hand, according to Chang S. (2011), very long SRT is not practical for the full-scale operation because of accumulation of inert and non-biodegradable compounds in the reactor.

In literature it is hard to find studies, which evaluate the MBR performance at short SRT. Ng et al. (2005)'s study is the first study that investigated short SRTs in MBR. Ng et al. operated a lab-scale submerged MBR using hollow fiber membranes and a completely mixed activated sludge (CMAS) system in paralel at SRT between 0.25 and 5 days feeding synthetic wastewater and observed COD removal ranging between 97.3 and 98.4 % with the MBR system.

Harper et al. (2006), studied the biomass characteristics and microbial yield with a lab-scale MBR system and a SBR system operated at SRT between 0.5 and 3 days. The study of Harper et al. (2006) confirmed the results of Ng et al. (2005) of higher amount of SS and higher effluent quality obtained in MBR systems.
After these studies, L. Duan et al. (2009) has investigated effects of short solids retention time (SRT = 3, 5 and 10 d) on reactor performance and microbial community composition in a lab-scale nitrifying membrane bioreactor. They reported that process was capable of achieving over 87% removal of ammonia and 95% removal of COD, almost regardless of SRT. In addition to these in the study investigated by L. Duan et al. (2009) has provide information about reactor microbial community with operated short SRTs.

The studies have reported conflicting results about relevance between long and short SRT effect on membrane fouling. Less fouling observed at long SRT is explained by lower concentration of EPS and SMP. This is supported with the studies of Song et al. (2007) who studied SRT of 10, 20, and 40 days in MBR. Song et al. (2007) explained that accumulation of SMP in the MBR became more pronounced at short SRTs therefore fouling potential of SMP considerably increased as SRT shortened. According to Song et al. (2007) the differences in fouling potential are supposed to originate from the different characteristics of SMP at different SRTs；Ahmed et al. (2007) who explains the higher TMP increase with high EPS levels obtained at SRT of 20 days compared to SRT of 40, 60 and 100 days. The increased membrane fouling at longer SRT is correlated with increase of SS concentrations and/or accumulation of non-biodegradable compounds in the system (Le- Clech et al., 2006).

On the other hand,Cicek et al., (2001) stated that a MBR can be operated at lower SRT of less than 10d. Another study that is performed by Ng et al. (2005), they found an inverse proportion with sludge age and fouling. Lee et al. (2003) have also reported that fouling is increased by increasing the SRT from 20 days to 60 days. Although many studies in the literature investigating the effect of SRT support the finding that longer SRT results in less fouling (Zhang et al.,2006; Ahmed et al., 2007; Liang et al., 2007), the relation (SMP, SS or bound EPS in the sludge or even at the surface of the membrane) has not been clearly described. This also depends on the definitions of SMP and bound/soluble EPS assumed in these studies and the methodologies used for the analysis (Al-Halbouni et al., 2008).

2.3.2 Effect of HRT on MBR performance

The HRT is the another important parameter MBR applications. HRT is related to the organic loading, shown as Substrate/Microorganisms (F/M) ratio, which is an important design and operation parameter and it is directly linked to the reactor volume and operating costs (Viero et al., 2008).

The shorter HRT means that higher OLR thus HRT has a significant impact on mixed liquor. Changes in mixed liquor both effect the treatment efficiency and fouling.

The effects of OLR on membrane fouling and biomass are summarized by Meng et al. (2007) as shown in Figure 2.5.

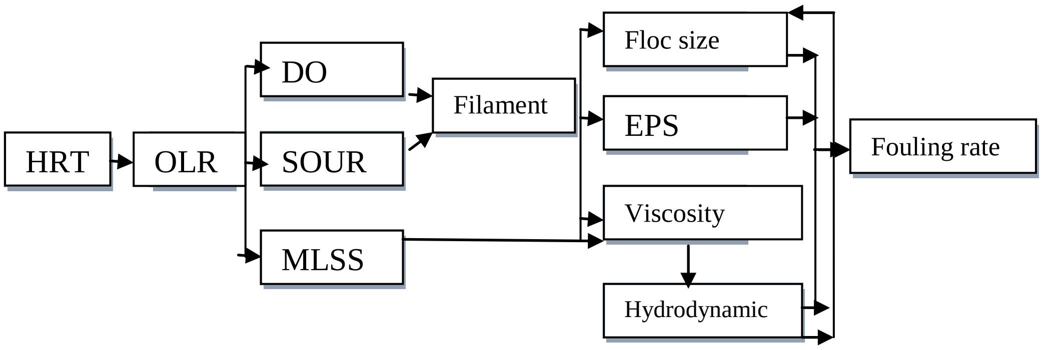

Figure 2.5 : Schematic relation of OLR with sludge characteristics and membraneperformance (Meng et al., 2007).

OLR plays an important role in MBR performance. Kornboonraksa and Lee (2009) reported that an increase of influent COD, BOD and NH4-N resulted in decreased in the removal efficiency of COD, BOD and NH4-N. Also Trussell et al. (2006) reported higher OLR resulted in increasing membrane fouling. In a recent study performed by Khoshfetrat (2011), it was found that when OLR increased from 1 to 2.5 kg COD/m3d, the COD removal efficiency reduced from 90% to 74%.

In the study performed by L.Dominguez et al.(2012), they operated the MBR systems with a volumetric organic loading rate of between 0.4 and 1.3 kg COD/m3d. They found that growth rate of MLSS increased when the loading rate increased and COD removal efficiency higher than 93% in both loading rates.

Meng et al. reported that the HRT did not change the removal of chemical oxygen demand (COD), but as the HRT decreased the biomass activity and thus the dissolved oxygen concentration in mixed liquor decreased. Cho et al. reported that the longer HRT reduced the membrane fouling. Chae et al.reported that a reduction in HRT, from 10 h to 4 h, resulted in an increase of EPS and the average particle size and increasing the membrane resistance.

In study performed by Hong et al. (2012) submerged hollow fiber membrane bioreactor operated for different HRTs (4, 2, 1.3 and 1 h) they found that shorter HRT developed higher trans-membrane pressure.

According to (Viero et all., 2008) working with a synthetic wastewater containing easily biodegradable compounds, they found that HRT has not influence COD removal efficiency .

In another recent study conducted by Johir et al. (2011), the MBR was operated with different OLRs between 0.5 and 3 kg COD/m3d, the HRT and SRT were kept at 8 h and 40 d, respectively, without changing any hydrodynamic parameters. In this study, Johir et al. (2011) found that the removal efficiency of DOC, COD and NH4-N decreased when OLRs increased from 0.5 to 3 kg COD/m3d. And they found that higher OLRs resulted in higher transmembrane pressure (TMP).

It is obvious that the development of TMP is related to the higher OLR. In literature this is associated with following reasons:

i. An increase of MLSS concentration (Cicek et al.,1999)
ii. An increase of non-flocculating microorganisms in sludge which is related with increasing of F/M ratio (Ng and Hermanowicz, 2005)
iii. The production of hydrophilic compounds which is attached onto the membrane surface

2.3.3 Membrane fouling and its relation with EPS/SMP

MLSS concentration was known as the first parameter which is responsible from fouling. Mostly increase in the concentration of MLSS, is known to have a negative impact on the MBR hydraulic performance (Le-Clech et al., 2006). Blockage caused by the increase in the concentration of MLSS in fact is associated with EPS and SMP formation in bulk solution.

In many studies, EPS is usually defined as “macromolecules such as polysaccharides, proteins, nucleic acids, lipids and other polymeric compounds” which is responsible from membrane fouling. SMP similarly is defined as “soluble cellular components in bulk solution”.

Generally EPS are classified according to their phase present in the activated sludge as (i) floc bound EPS, and (ii) soluble EPS in the water phase of sludge mostly known as SMP. The EPS found in MBR sludge is not much different from the one reduced in a conventional system however, the amount of SMP in MBR sludge is reported to be higher (Masse et al., 2006). SMP is considered under two categories; (i) biomass related products produced from endogenous respiration/decay of biomass and (ii) growth related products resulting from utilization of substrate (Laspidou and Rittman, 2002).

There are conflicting results presented in the literature regarding the effects of the above mentioned physical and chemical properties on membrane fouling. Some studies report that there is a positive relationship between EPS concentration and fouling (Chang ve Lee, 1998; Chang et al., 2001), whereas others claim the opposite (Le-Clech et al., 2006) and some studies found no correlation (Rosenberger and Kraume, 2003; Yamato et al., 2006; Geng et al., 2007).

In the study performed by Song et al. (2007), they operated laboratory-scale MBR at SRT of 10, 20 and 40 days for treatment of readily biodegradable synthetic wastewater. In all SRTs they found the COD removal efficiencies excellent and stable results around 95 % and accumulation of SMP became pronounced at short SRTs. In this study another notable point was that metabolic activity of sludge which has characterized by specific oxygen uptake rate (SOUR), decreased when SRT increased. Another study conducted by Hollender et al. (2007) , they operated full-scale MBR system with the SRTs 23 d and 40d it was found that a high molecular weight (MW) fraction of EPS has detected at lower SRT.

Many studies are found in the literature on membrane fouling especially on the suspended, colloidal and soluble fractions of sludge affecting membrane fouling. Fouling rate is reported to be increased with increasing MLSS concentration (Yigit et al., 2008). Studies have shown that amount of suspended solids (SS) in the reactor around 2-24 g/L may affect fouling. Defrance et al., (2000) reported that the membrane fouling is 65 % resulting from SS. Nagaoka et al. (1996); Fan et al. (2006) and Defrance et al. (2000), are claiming that the effects of colloidal organic matter are higher than the soluble organics, whereas Wisniewski and Grasmick (1998); Bouhabila et al. (2001) relate filtration resistance primarily to the soluble organic matter content.

Drews et al. (2008), found no relation between the polysaccharide concentration and fouling and claimed to confirm the literature findings that said the effect of SMP is less related to fouling and filtration resistance at longer SRT. The results showed that SMP affects fouling only at short SRT and large pore sizes.

Tao (2008), found that the biomass related products and growth related products in MBR have extreme fouling potential. According to Tao (2008), majority of SMP is of slowly biodegradable character and SMP is accumulated as it is retained by the membrane. The high fouling potential of SMP is explained by their small size, which allows their deposition on membrane surfaces. Deposited SMP causes clogging of the pores and formation of cake.

3. MATERIALS and METHODS

3.1 Experimental Set-up and Operation

A lab scale submerged MBR (sMBR) system equipped with hallow fiber Zee Weed*1 (GE) membrane module was used in the study. The surface area of the MBR module was 0.1m^2 and it had a pore size of 0.04µm. Table 3.1. summarizes the membrane's properties and operating specifications.

Table 3.1 : Membrane properties and operating specifications.

Module Type	
Nominal Membrane Surface Area	1 ft^2(0.1 m^2)
Module Dimensions	
Heigh	175mm
Diameter	56 mm
Membrane Properties	
Material	PVDF
Nominal Pore Size	0.04 micron
Surface Properties	Non-Ionic& Hydrophilic
Fiber Diameter	1.9 mm OD/ 0.8 mm ID
Flow Path	Outside-In
Operating Specifications	
TMP Range	-55 to 55 kPa (-8 to 8 psi)
Max. Operating Temperature	40◦C (104 F)
Operating pH Range	5.0- 9.5
Cleaning Specifications	
Max. Cleaning Temperature	40C (104 F)
Cleaning pH Range	2.0- 10.5
Max. CI_2 Concentration	1.000 ppm

A lab-scale sMBR with a bioreactor having 3 L operating volume coupled with an ultrafiltration (UF) submerged membrane module was designed and installed in the laboratory. The scheme of the lab scale MBR is shown in Figure 3.1 The system was operated under the HRT of 8 hours and at constant flux at all experimental runs, with SRT ranging from 0.5 d – 2.0 d. HRT selected reflected the lowest HRT applicable to the membrane module used in the system for long term operation. Two different synthetic substrate feedings were tested; (a) soluble/readily biodegradable substrate mixture and (b) acetate. The synthetic mixture representing readily biodegradable COD in wastewater was tested at all SRTs, whereas synthetic feed constituting only acetate was tested only at SRT of 1.0 day. The synthetic feeds were adjusted to first 200 mg COD/L and than 1000 mg COD/L for the experimental runs.

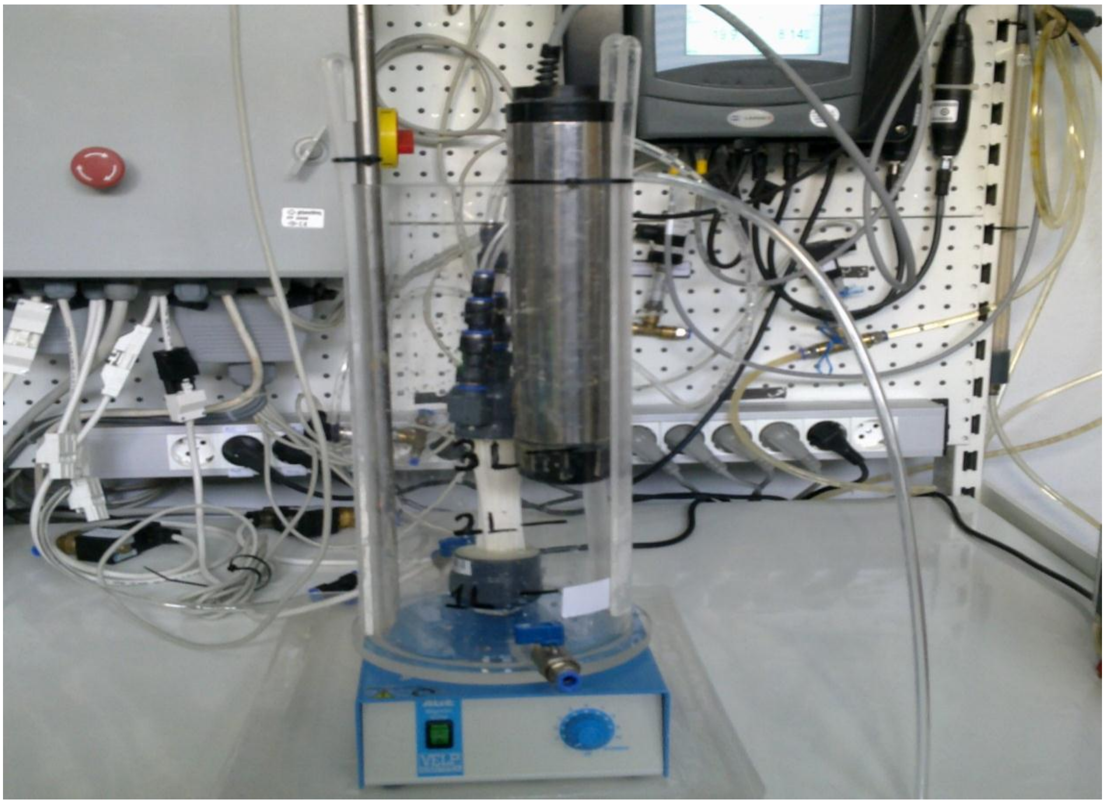

Figure 3.1 : The scheme of the experimental set-up.

The lab-scale sMBR was automatically controlled by means of a Programmable Logic Controller (PLC) as shown in Figure 3.2, in order to constantly control and measure the principal operational variables: dissolved oxygen (DO), transmembrane pressure (TMP), pH and temperature.

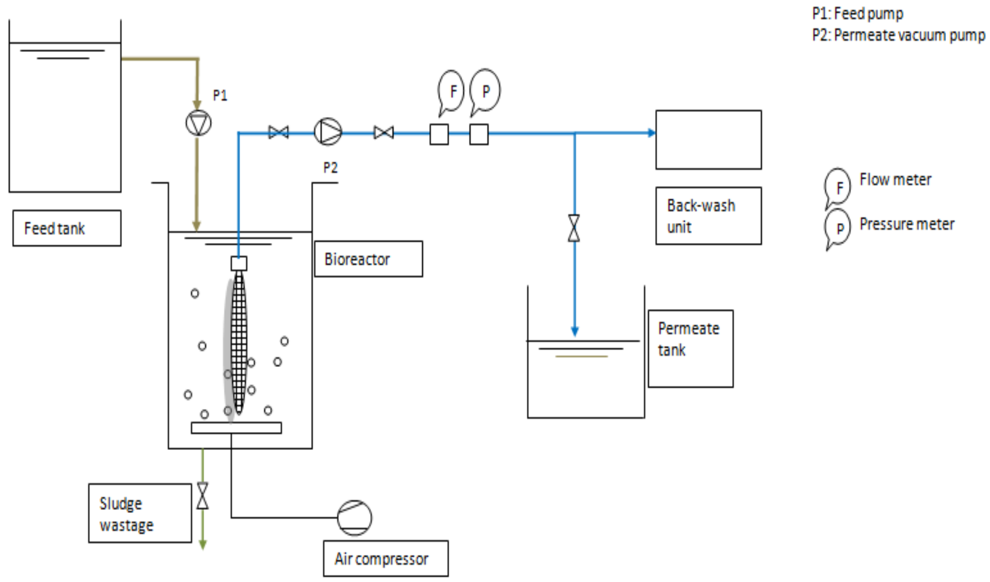

Figure 3.2 : Process flow scheme of the lab-scale MBR.

The system was started up by inoculating sludge from a fill and draw reactor fed with same composition of synthetic wastewater and operated at SRT of 2.0 d. While acclimating the biomass, which is grown and acclimatised in a fill and draw reactor, to the specific synthetic wastewater to be used in the experimental runs, all other macro and micronutrients necessary for biological growth were added into the reactors in sufficient quantities. Nutrient requirements of the activated sludge were supplied with the addition of the Solution A and Solution B (O'Connor, 1972). 10 ml of Solution A and 10 ml of Solution B is added to the reactor for a synthetic feed with a COD concentration of 1000 mgCOD/l. The components Solution A and Solution B are given in Table 3.2.

Table 3.2 : Composition of Solution A and B.

Solution	Component	Amount of Component (g/l)
Solution A	NH_4Cl	120
	KH_2PO_4	160
	K_2HPO_4	320
Solution B	$MgSO_4.7H_2O$	15
	$CaCl_2.7H_2O$	2
	$FeSO_4.7H_2O$	0.5
	$ZnSO_4.7H_2O$	0.5
	$MnSO_4.H_2O$	0.5

3.2 Organic Substrate Compositions Used in the Experiments

Two different synthetic substrate feedings were tested to control the influent into the MBR and to operate MBR at a constant influent volumetric organic load. The first synthetic feed was the soluble/readily biodegradable substrate mixture consisting of acetic acid, propionic acid, ethanol, glutamic acid and glucose used as suggested by Sözen et al. (1998) and Henze (1992) and the composition is shown in Table 3.3.

Table 3.3 : Synthetic wastewater composition representing readily biodegradable COD fraction.

Composition	Fraction (% COD)
Acetic acid	41
Propionic acid	17
Ethanol	8
Glutamic acid	17
Glucose	17

A stock solution for the synthetic feeds was prepared (36,000 mg COD/L) and fed to the system continuously at a concentration of 200 mg COD/L and 1000 mg COD/L.

The second synthetic feed constituted only acetate as substrate.

3.3 Analytical Methods

Samples taken for COD from the bioreactor and the permeate are filtered through 0.45 μm PVDF syringe filters and preserved with H_2SO_4 if necessary. The COD samples were analyzed according to ISO6060 methodology (ISO 6060, 1986). Mixed liquor suspended solids (MLSS) and volatile suspended solids (MLVSS) concentrations were determined according to Standard Methods (AWWA, 2005).

3.3.1 Respirometric measurements

Oxygen Uptake Rate profiles are obtained by using a respirometer (RA-1000; Manotherm). Respirometric analyses are made using the MBR activated sludge (2L) by employing the same F/M conditions applied to the original MBR bioreactor. The activated sludge from the respirometer chamber is continuously passed through the respiration vessel (0.75 L), where the dissolved oxygen at the inlet and outlet are measured, the sample is returned back to the chamber. The OUR is calculated based on the measurements of a single DO-electrode where the measuring frequency is limited by the response rate of the DO-electrode (Spanjers and Klapwijk, 1990) and is fixed once a minute. The possible interference of ammonia consumption for nitrification is avoided by adding thiourea which inhibits nitrification.

The details of experimental conditions for the systems fed with both readily biodegradible COD composition and acetate composition of OUR tests are given in Table 3.4.

Table 3.4 : Substrate, concentration and ratio of substrate to microorganism.

	Influent Wastewater Concentration (mg COD/L)	**SRT (day)**	**S_0/X_0 (mg COD/ mg VSS)**
Readily Biodegradible Mixture Composition	200	2.0	0.45
		1.0	0.57
		0.5	0.72
	1000	2.0	0.41
		1.0	0.57
		0.5	0.88
Acetate	200	1.0	0.5
	1000	1.0	0.5

3.3.2 SMP and EPS analysis

SMP and EPS analysis were made with samples taken from the mixed liquor from the bioreactor. The important point in EPS and SMP analysis is to separate these components without damaging the cells. In order to achieve this physical-chemical (sodium hydroxide-formaldehyde) extraction method was used. Formaldehyde prevents the cell rupture while it reacts with the nucleic acid and amino, hydroxyl, carboxyl and sulfide groups of proteins present in the cell wall. Hence cell forms are preserved. NaOH increases the pH which increases the solubility of EPS in water and increases the amount of EPS to be extracted from the cells (Liu and Fang, 2002).

At the first stage of the analysis, sludge sample is centrifuged at a lower speed allowing bacteria to be removed from the medium. The supernatant is centrifuged at high speed and the SMP released from the cell to the medium is physically separated from the water phase. Separation of EPS, which is attached to the bacterial cells, is possible by adding the above mentioned chemicals during the procedure. After separation of SMP and EPS, samples are analyzed for protein and carbohydrate contents.

Samples are taken from the bioreactor for EPS and SMP analysis, while permeate sample is analyzed only for SMP. Samples of 5 ml volumes are taken and placed in Eppendorf tubes. These samples are centrifuged for 10 minutes at 4°C at 4000 ×g in order to remove the suspended solids. The supernatant obtained is transferred to a sterile tube and re-centrifuged for 20 minutes at 4°C at 13200 ×g. The supernatant obtained from this physical separation is analyzed for soluble protein and carbohydrate. The sum of soluble protein and carbohydrate corresponds to the SMP (free EPS) present in the medium. In order to determine the bound EPS, the residue retained after the first centrifuge is completed to 5 mL volume by adding distilled water. 6 µL formaldehyde (%37) is added and the solution is kept at 4°C for 1 hour. Following this, 500 µL NaOH (1N) is added and the solution is kept at 4°C for another 3 hours. The suspension is centrifuged at 13200 ×g and 4°C for 20 minutes. The supernatant obtained from the chemical extraction is analyzed for carbohydrates and proteins, the sum of which will give the bound and/or extracted EPS. Lowry method is used for the analysis of proteins and phenol-sulfuric acid method is used for the analysis of carbohydrates (Dubois et al., 1956).

According to the Lowry method, three main solutions were prepared to be used for the analysis (Solutions A, B and C). For preparation of Solution A, 2.86 g of NaOH and 14.31 g of Na_2CO_3 are dissolved in distilled water and completed to a final volume of 500 mL. For preparation of Solution B, 1.42 g of $CuSO_4.5H_2O$ is dissolved in 100 mL distilled water. For the preparation of Solution C, 2.85 g of Na_2tartarate.$2H_2O$ is dissolved in 100 mL distilled water. Lowry solution is prepared on the analysis day by mixing of Solutions A, B and C with the ratio of 100:1:1 (A:B:C). 0.7 ml of the Lowry solution is added to 0.5 ml of sample, the mixture is mixed rigorously and let still for 20 minutes at room temperature at dark. Folin solution is prepared in parallel by adding 5 ml of 2N folin to 6 ml of distilled water. 0.1 ml of folin solution is added to each 0.5 ml sample after which the samples are mixed rigorously and let still for 30 minutes at room temperature at dark. At the end of this period the samples are colored from light to dark blue according to their protein contents. The colorimetric analyses were made by using Spectro Pharmacia LKB Nova Spec II UV spectrophotometer at 660 nm against a blank sample. In order to assure reproducibility two analysis samples were prepared from the original sample.

Bovin Serum Albumin (BSA) was used as the standard protein solution for the preparation of the protein calibration curve. Solutions of BSA, with concentrations in the range between 5-50 mg/L were prepared. The absorbance values read at 660 nm wavelength with the UV Spectophotometer were plotted against the standard concentrations. The calibration curve is given in Figure 3.3.

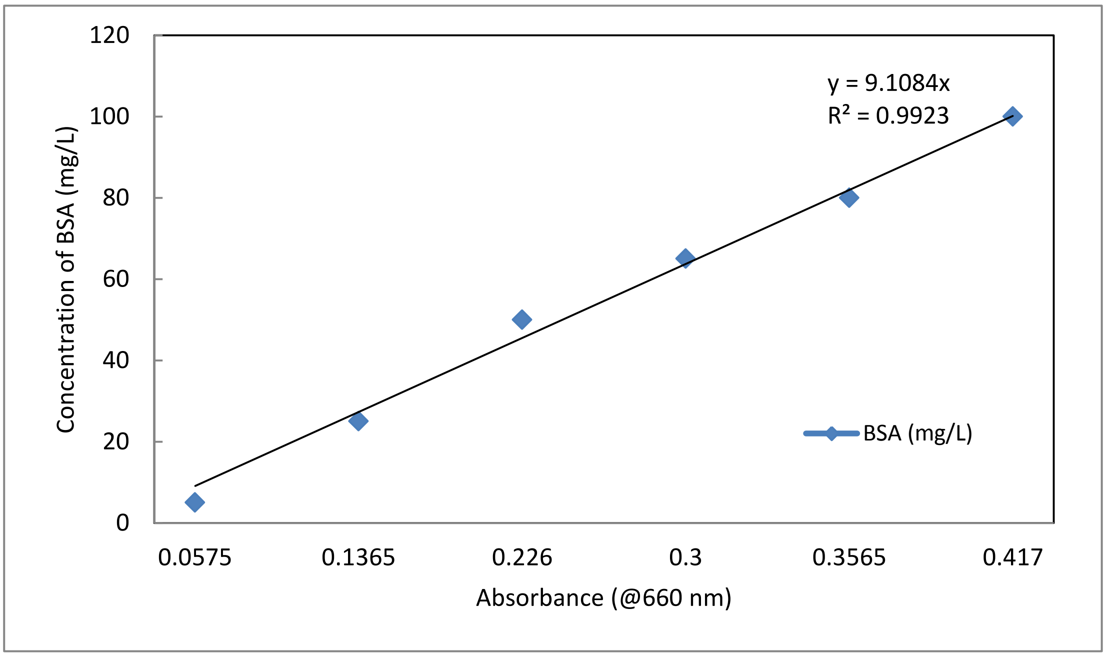

Figure 3.3 : Protein calibration curve.

Modified "phenol-sulphiric acid method" (Dubois) was used for the analysis of carbohydrates. For the analysis 80% phenol solution and concentrated H_2SO_4 (95-97 %) were used. 25 µL of 80% phenol solution and 2.5 mL of H_2SO_4 was added to 1 ml of sample and the sample was let still for 15 minutes at 30^{0}C water bath. At the end of this period the samples are colored from light to dark yellow according to their carbohydrate contents. The colorimetric analyses were made by using Spectro Pharmacia LKB Nova Spec II UV spectrophotometer at 490 nm wavelength against a blank sample.

Glucose was used as the standard carbohydrate solution for the preparation of the carbohydrate calibration curve. Solutions of standard glucose, with concentrations in the range between 2-80 mg/L were prepared. The absorbance values read at 490 nm wavelength with the UV Spectophotometer were plotted against the standard concentrations. The calibration curve is given in Figure 3.4.

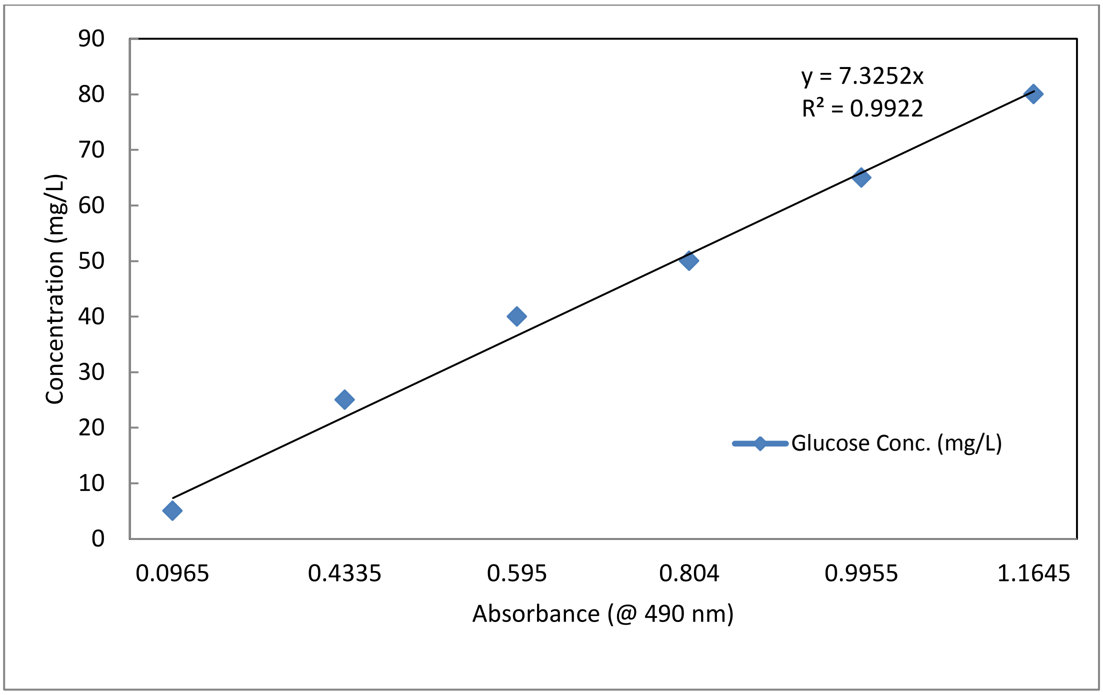

Figure 3.4 : Carbohydrate calibration curve.

3.3.3 Analysis of storage products

PHB samples were taken into centrifuge tubes containing 2 drops formaldehyde for preventing the biological activity. The PHB content of the washed (K-P buffer solution) and freeze-dried biomass were subjected to extraction, hydrolization, and esterification in a mixture of hydrochloric acid, 1-propanol, and dichloroethane at 100°C (Beun et al., 2000). The resulting organic phase was extracted with water to remove free acids. The propylesters were analyzed by gas chromatograph (GC Agilent 6890 N) according to methodology described by Beun et al.,2000. Benzoic acid was used as an internal standard throughout the procedure.

3.3.4 Capillary suction time (CST)

A CST apparatus (Triton, W.P.R.L Type:92/1) was used to determine the dewatering characteristics of the sludge samples, which measures the time the filtrate requires to travel a fixed distance in the filter paper which is referred to as CST. The apparatus (Figure 3.5) consists of a timing device, an upper plate containing probes that activate and deactivate the timing device, and a lower plate that holds the filter paper and a metal sample container. 5 ml of sludge sample was placed in the sample container, which activates the timer when it reaches to the first probe. The times deactivates when the sample reaches the second probe. The time interval between timer activation and deactivation was the recorded as the capillary suction time.

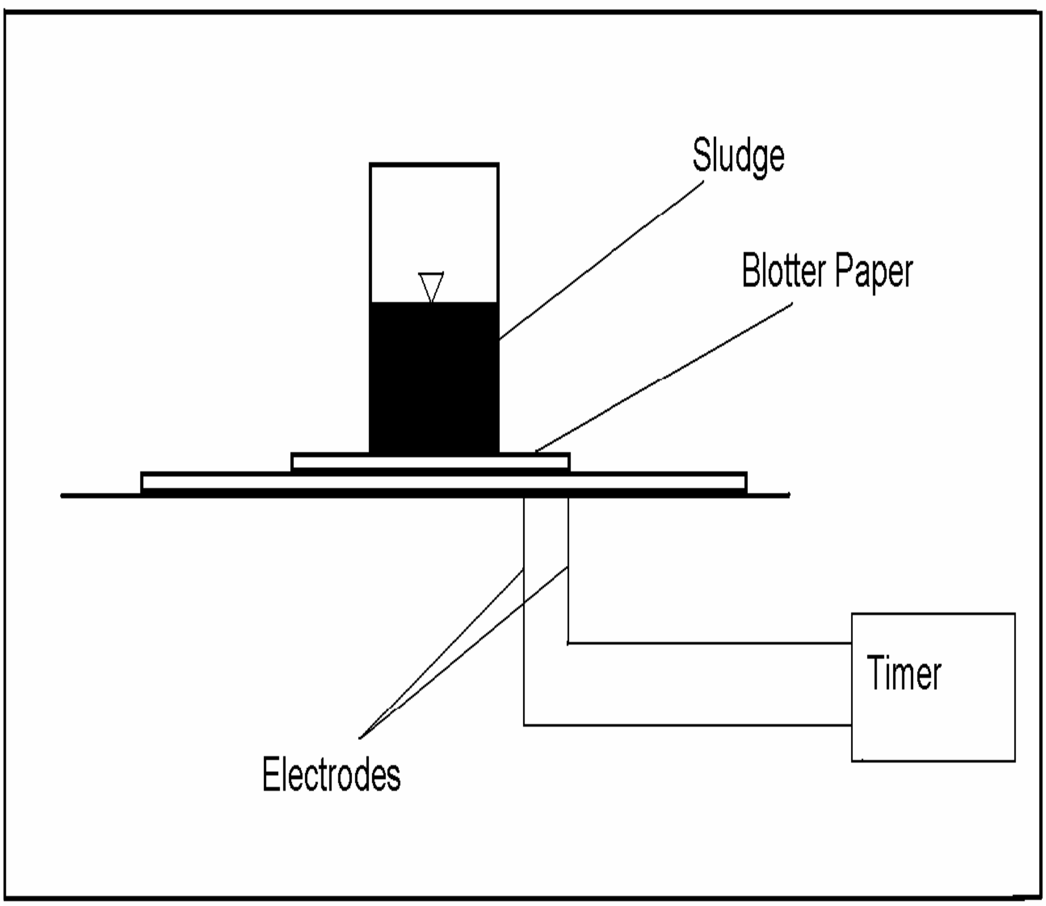

Figure 3.5 : The sheme of CST.

4. RESULTS

4.1 MBR Operating Conditions

The experimental MBR runs were essentialy sustained at steady-state at three different SRTs; SRT of 2.0, 1.0 and 0.5 days, fed with two different synthetic feeds (substrate mixture solution representing readily biodegradable soluble COD of domestic wastewater and acetate solution) and different feed concentrations (200 and 1000 mg COD/ L) as described earlier, all operated at the HRT of 8 hours.

The MBR system operating conditions are summarized in Table 4.1.

Table 4.1 : MBR system operating conditions.

Parameters	**Readily Biodegradible Substrate**	**Acetate**
SRT (d)	2.0, 1.0, 0.5	1.0
Substrate concentration (mg COD/L)	200-1000	200-1000

System performance at steady-state was evaluated in terms of COD measurements in both reactor and permeate during all operation periods. COD inside the reactor was measured as soluble COD (SCOD-R) which was analyzed as filtered from 0.45µm syringe filter and as effluent COD (COD-P) which was analyzed as sampled.

4.2 Monitoring of MBR Performance

4.2.1 Monitoring of carbon removal and biomass generation

4.2.1.1 Operating conditions: Readily biodegradable substrate of 200 mg COD/L and SRT = 2.0 d

After a 15 day monitoring period, stable results could be reported for MLVSS, SCOD-R and COD-P profiles and the system was assumed to reach the steady state.

Figure 4.1 and Figure 4.2 show the performance profiles based on measured MLVSS, SCOD-R and COD-P, obtained from this experimental run with the sMBR.

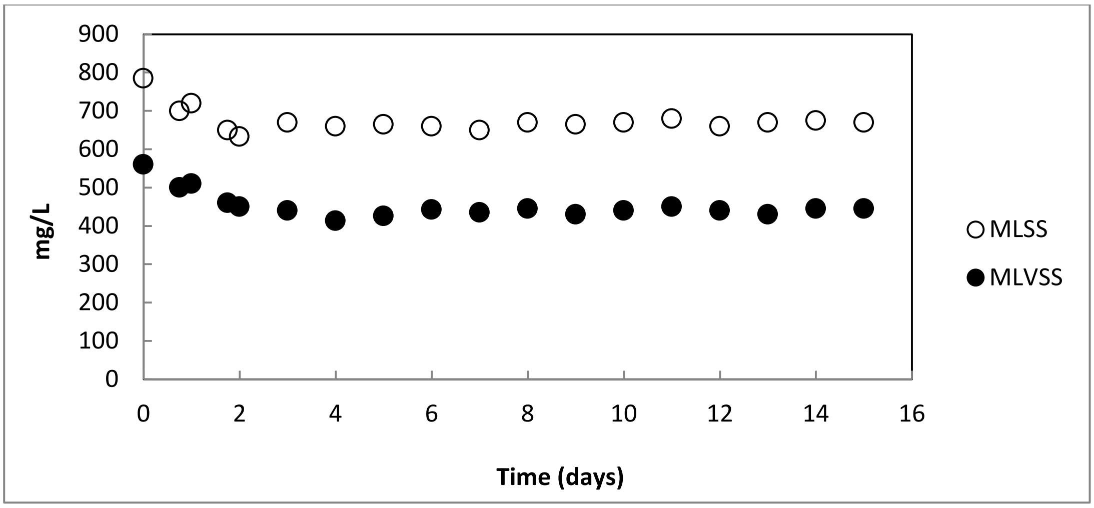

Figure 4.1 : MLSS and MLVSS profiles operated under readily biodegradable substrate of 200 mg COD/L and SRT = 2.0 d.

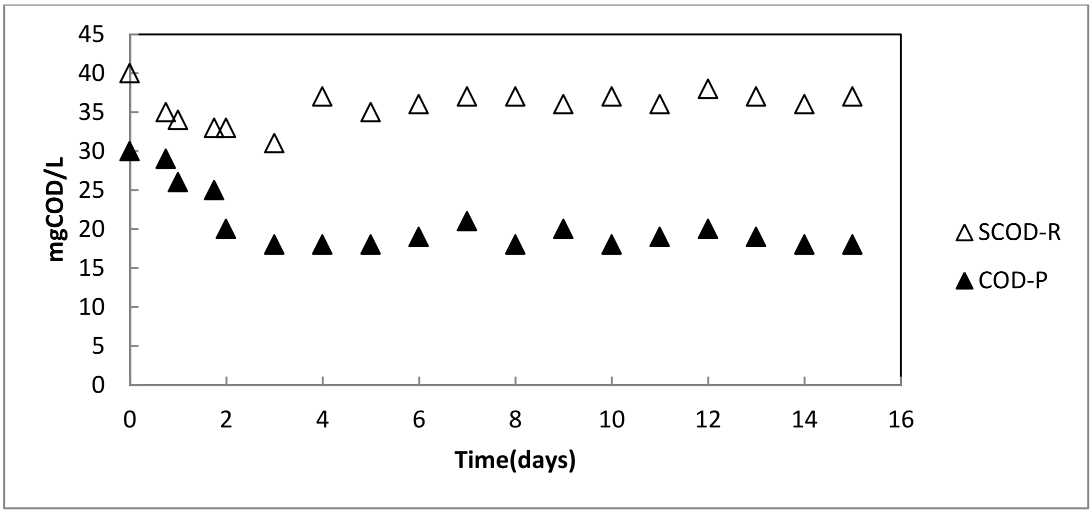

Figure 4.2 : Soluble reactor and permeate COD operated under readily biodegradable substrate of 200 mg COD/L and SRT = 2.0 d.

As seen from Figure 4. 1, the steady state MLVSS was around 450 mg MLVSS/L where as SCOD-R and COD-P were 37 mg COD/L (82 % COD removal efficiency) and 20 mg COD/L (90 % COD removal efficiency), respectively.

4.2.1.2 Operating conditions: Readily biodegradable substrate of 200 mg COD/L and SRT = 1.0 d

After a 12 day monitoring period, stable results could be reported for MLVSS, SCOD-R and COD-P profiles and the system was assumed to reach the steady state.

Figure 4.3 and Figure 4.4 show the performance profiles based on measured MLVSS, SCOD-R and COD-P, obtained from this experimental run with the sMBR

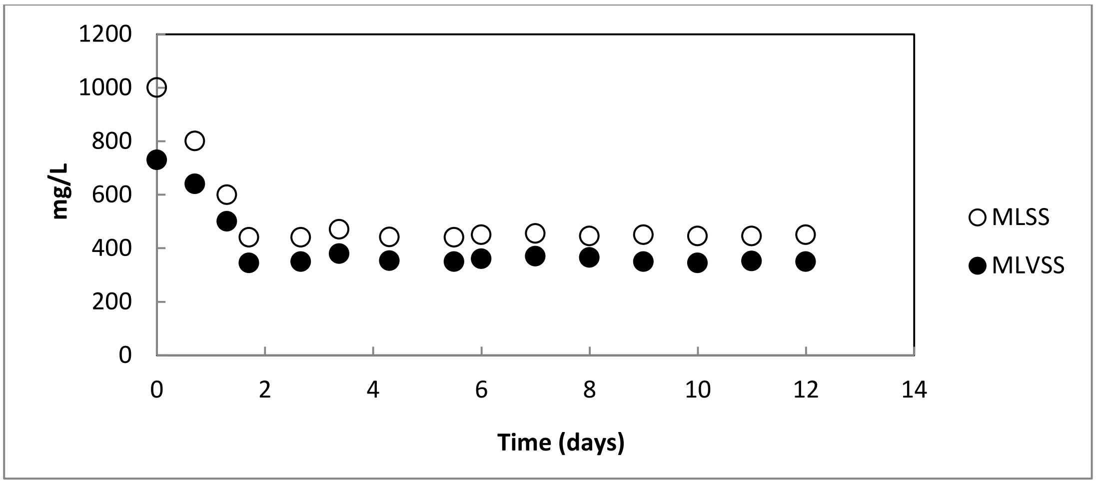

Figure 4.3 : MLSS and MLVSS profiles operated under readily biodegradable substrate of 200 mg COD/L and SRT = 1.0 d.

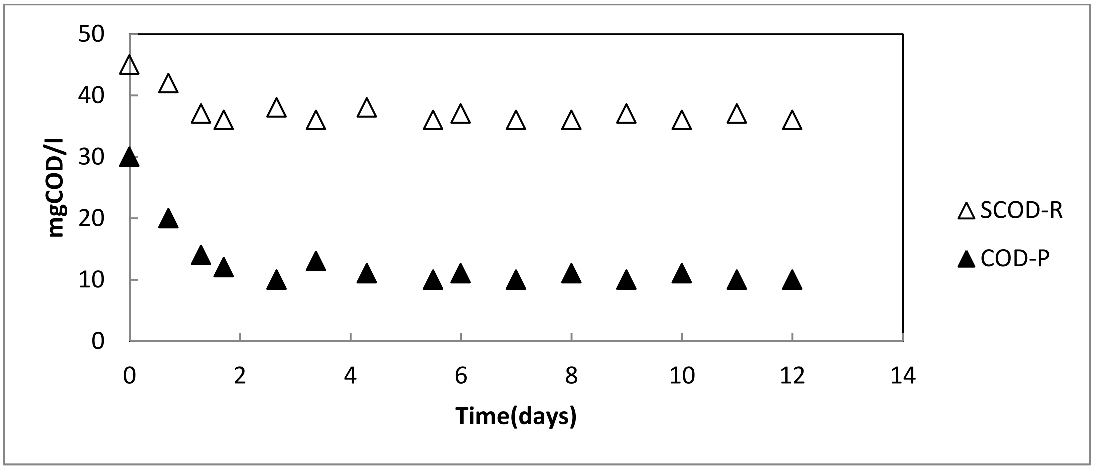

Figure 4.4 : Soluble reactor and permeate COD operated under readily biodegradable substrate of 200 mg COD/L and SRT = 1.0 d.

As seen from Figure 4. 3, the steady state MLVSS was around 350 mg MLVSS/L where as SCOD-R and COD-P were 36 mg COD/L (82 % COD removal efficiency) and 10 mg COD/L (95 % COD removal efficiency), respectively.

4.2.1.3 Operating conditions: Readily biodegradable substrate of 200 mg COD/L and SRT = 0.5 d

After a 10 day monitoring period, stable results could be reported for MLVSS, SCOD-R and COD-P profiles and the system was assumed to reach the steady state. Figure 4.5 and Figure 4.6 show the performance profiles based on measured MLVSS, SCOD-R and COD-P, obtained from this experimental run with the sMBR.

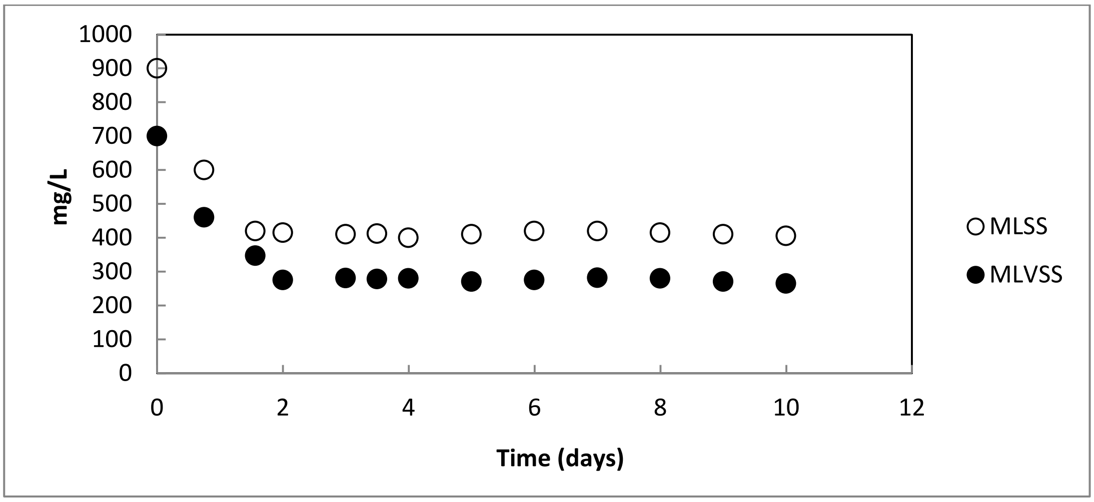

Figure 4.5 : MLSS and MLVSS profiles operated under readily biodegradable substrate of 200 mg COD/L and SRT = 0.5 d.

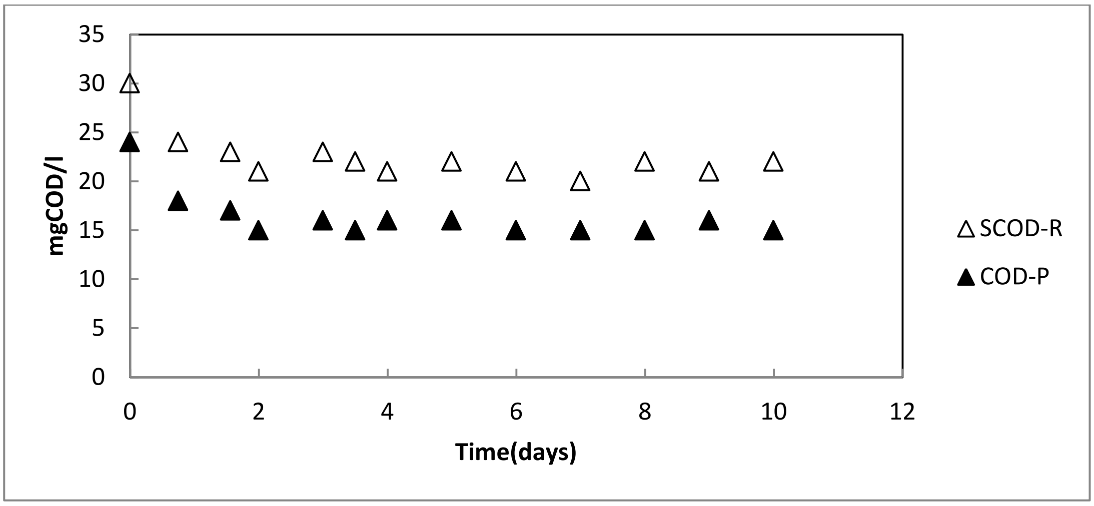

Figure 4.6 : Soluble reactor and permeate COD operated under readily biodegradable substrate of 200 mg COD/L and SRT = 0.5 d.

As seen from Figure 4.5, the steady state MLVSS was around 280 mg MLVSS/L where as SCOD-R and COD-P were 22 mg COD/L (89 % COD removal efficiency) and 15 mg COD/L (93 % COD removal efficiency), respectively.

4.2.1.4 Operating conditions: Readily biodegradable substrate of 1000 mg COD/L and SRT = 2 d

After a 15 day monitoring period, stable results could be reported for MLVSS, SCOD-R and COD-P profiles and the system was assumed to reach the steady state.

Figure 4.7 and Figure 4.8 show the performance profiles based on measured MLVSS, SCOD-R and COD-P, obtained from this experimental run with the sMBR.

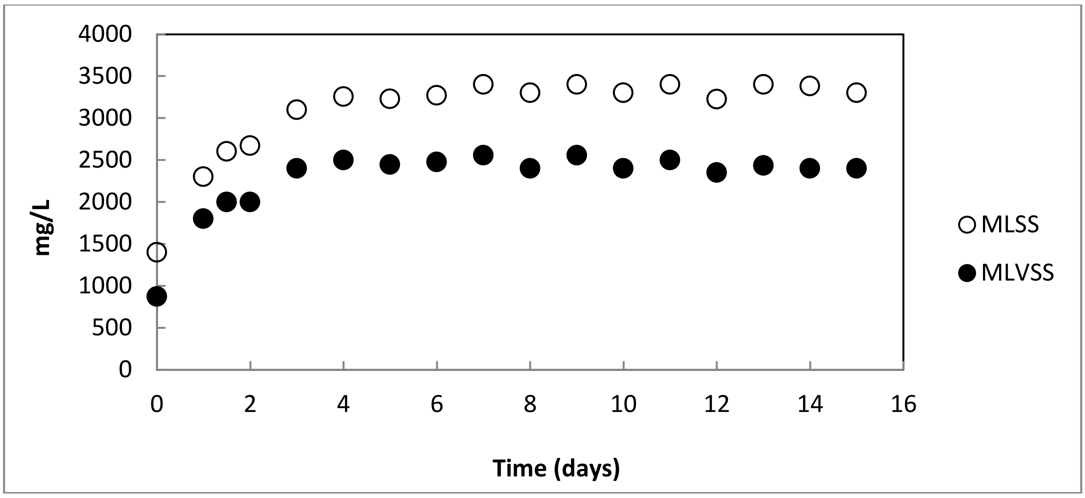

Figure 4.7 : MLSS and MLVSS profiles operated under readily biodegradable substrate of 1000 mg COD/L and SRT = 2.0 d.

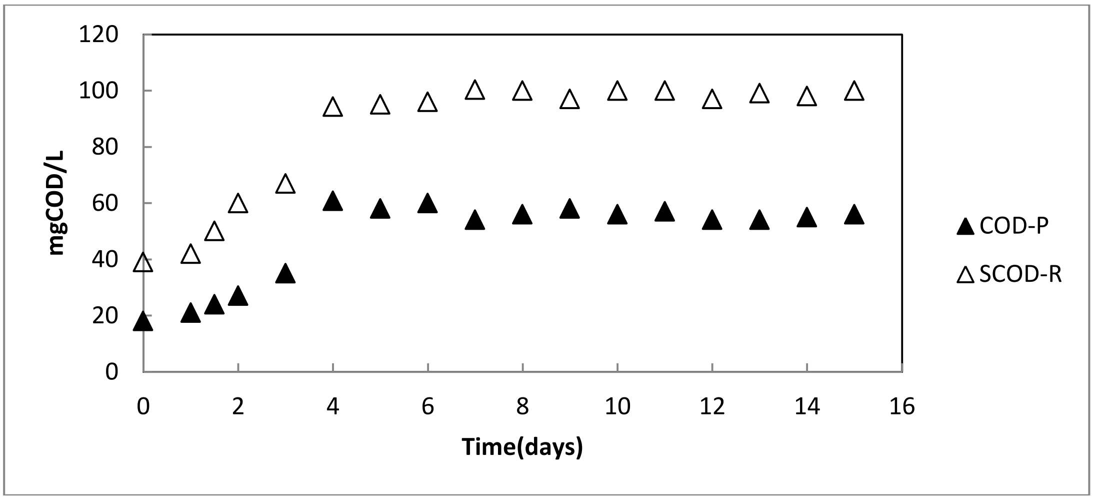

Figure 4.8 : Soluble reactor and permeate COD operated under readily biodegradable substrate of 1000 mg COD/L and SRT = 2.0 d.

As seen from Figure 4.7, the steady state MLVSS was around 2400 mg MLVSS/L where as SCOD-R and COD-P were 100 mg COD/L (90 % COD removal efficiency) and 56 mg COD/L (94.4 % COD removal efficiency), respectively.

4.2.1.5 Operating conditions: Readily biodegradable substrate of 1000 mg COD/L and SRT = 1.0 d

After a 12 day monitoring period, stable results could be reported for MLVSS, SCOD-R and COD-P profiles and the system was assumed to reach the steady state.

Figure 4.9 and Figure 4.10 show the performance profiles based on measured MLVSS, SCOD-R and COD-P, obtained from this experimental run with the sMBR.

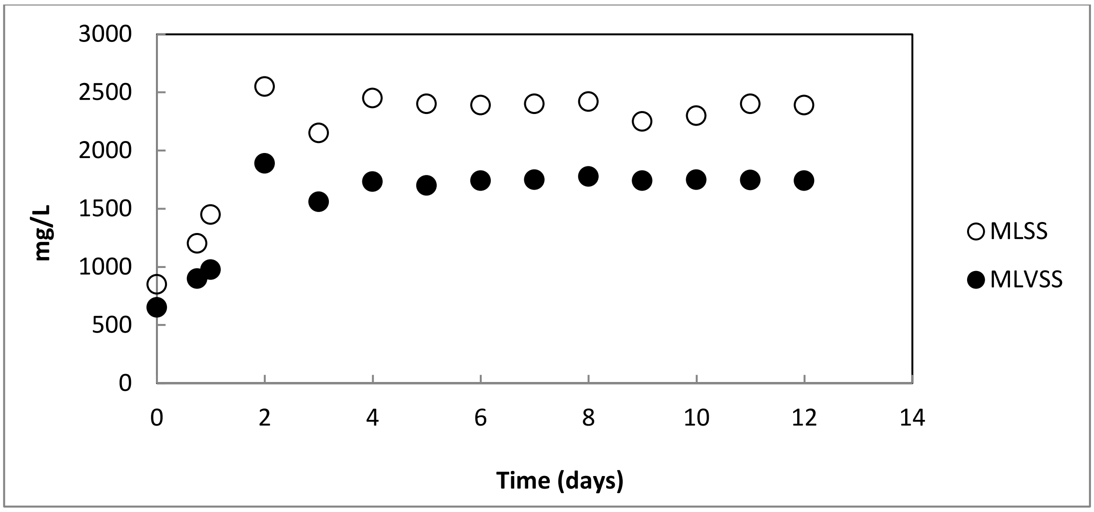

Figure 4.9 : MLSS and MLVSS profiles operated under readily biodegradable substrate of 1000 mg COD/L and SRT = 1.0 d.

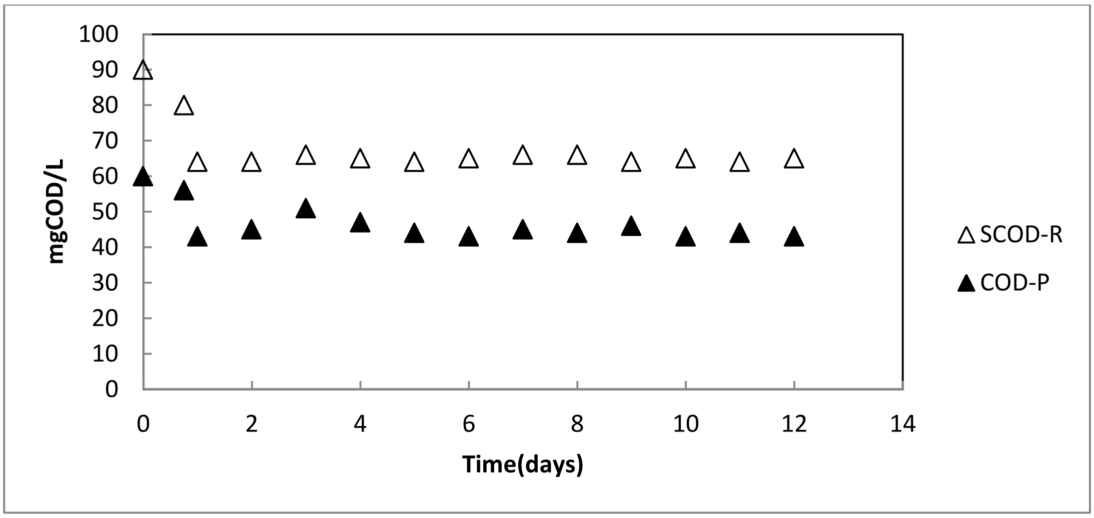

Figure 4.10 : Soluble reactor and permeate COD operated under readily biodegradable substrate of 1000 mg COD/L and SRT = 1.0 d.

As seen from Figure 4.9, the steady state MLVSS was around 1740 mg MLVSS/L where as SCOD-R and COD-P were 65 mg COD/L (93.5 % COD removal efficiency) and 45 mg COD/L (95.5 % COD removal efficiency), respectively.

4.2.1.6 Operating conditions: Readily biodegradable substrate of 1000 mg COD/L and SRT = 0.5

After a 10 day monitoring period, stable results could be reported for MLVSS, SCOD-R and COD-P profiles and the system was assumed to reach the steady state.

Figure 4.11 and Figure 4.12 show the performance profiles based on measured MLVSS, SCOD-R and COD-P, obtained from this experimental run with the sMBR.

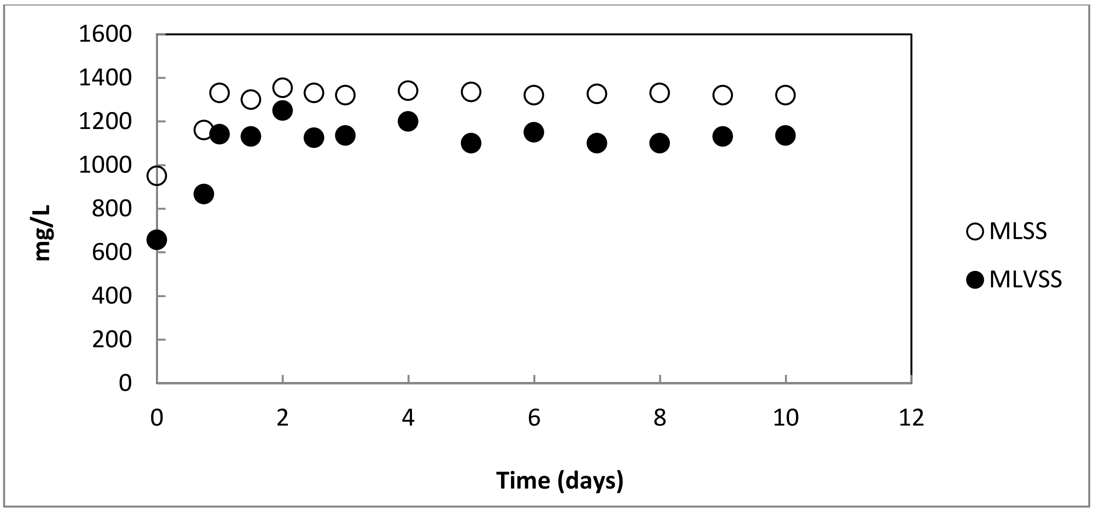

Figure 4.11 : MLSS and MLVSS profiles operated under readily biodegradable substrate of 1000 mg COD/L and SRT = 0.5 d.

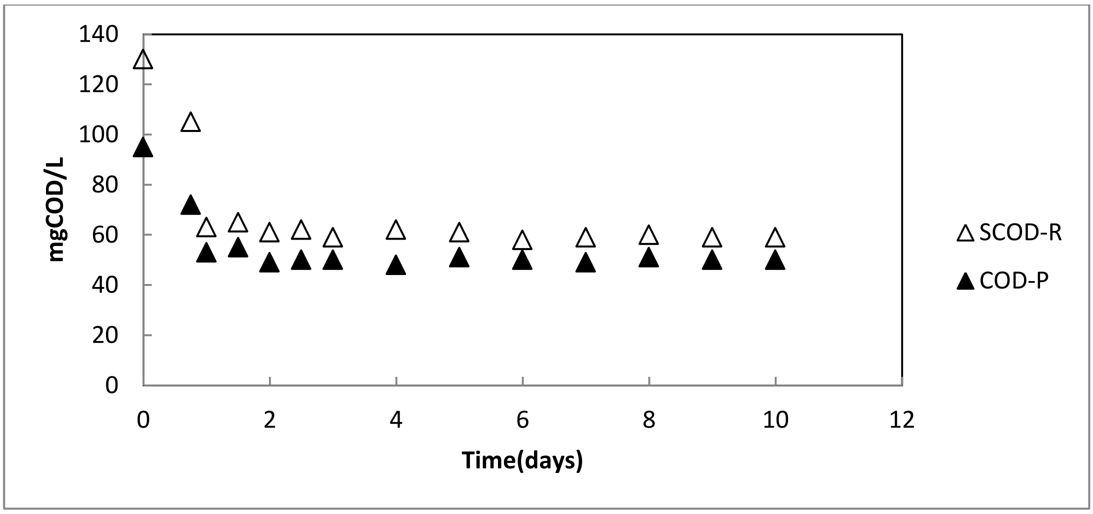

Figure 4.12 : Soluble reactor and permeate COD operated under readily biodegradable substrate of 1000 mg COD/L and SRT = 0.5 d.

As seen from Figure 4.11, the steady state MLVSS was around 1135 mg MLVSS/L where as SCOD-R and COD-P were 59 mg COD/L (94 % COD removal efficiency) and 50 mg COD/L (95 % COD removal efficiency), respectively.

4.2.1.7 Operating conditions: Acetate of 200 mg COD/L and SRT = 1.0 d

After a 12 day monitoring period, stable results could be reported for MLVSS, SCOD-R and COD-P profiles and the system was assumed to reach the steady state. Figure 4.13 and Figure 4.14 show the performance profiles based on measured MLVSS, SCOD-R and COD-P, obtained from this experimental run with the sMBR.

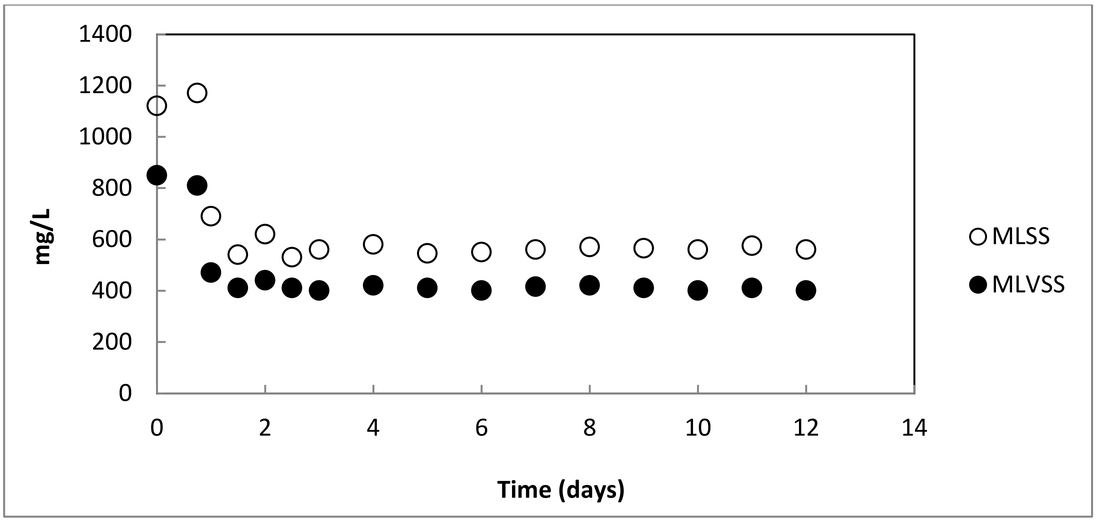

Figure 4.13 : MLSS and MLVSS profiles operated under acetate of 200 mg COD/L and SRT = 1.0 d.

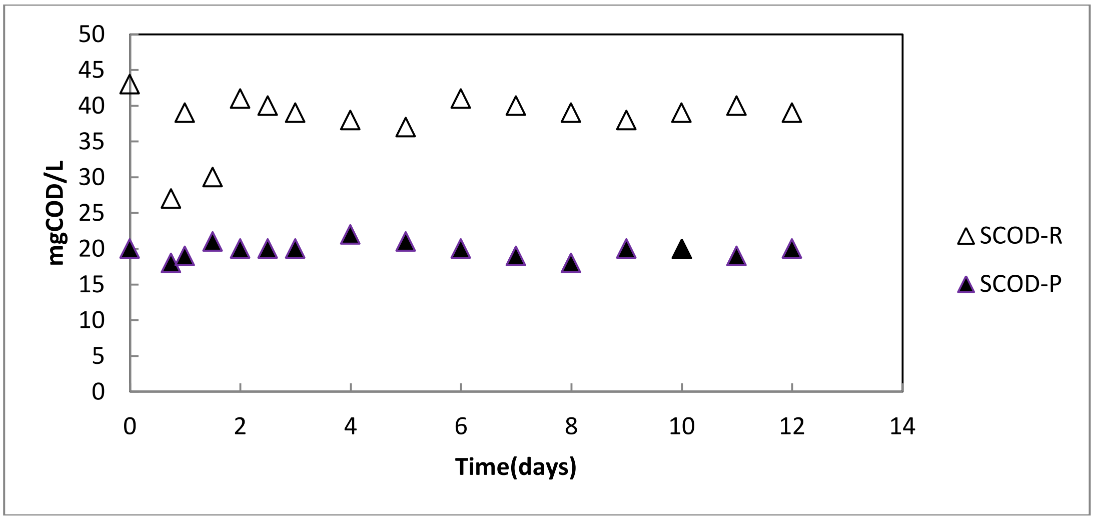

Figure 4.14 : Soluble reactor and permeate COD operated under acetate of 200 mg COD/L and SRT = 1.0 d.

As seen from Figure 4.13, the steady state MLVSS was around 400 mg MLVSS/L where as SCOD-R and COD-P were 39 mg COD/L (80.5 % COD removal efficiency) and 20 mg COD/L (90 % COD removal efficiency), respectively.

4.2.1.8 Operating conditions: Acetate of 1000 mg COD/L and SRT = 1.0 d

After a 12 day monitoring period, stable results could be reported for MLVSS, SCOD-R and COD-P profiles and the system was assumed to reach the steady state. Figure 4.15 and Figure 4.16 show the performance profiles based on measured MLVSS, SCOD-R and COD-P, obtained from this experimental run with the sMBR.

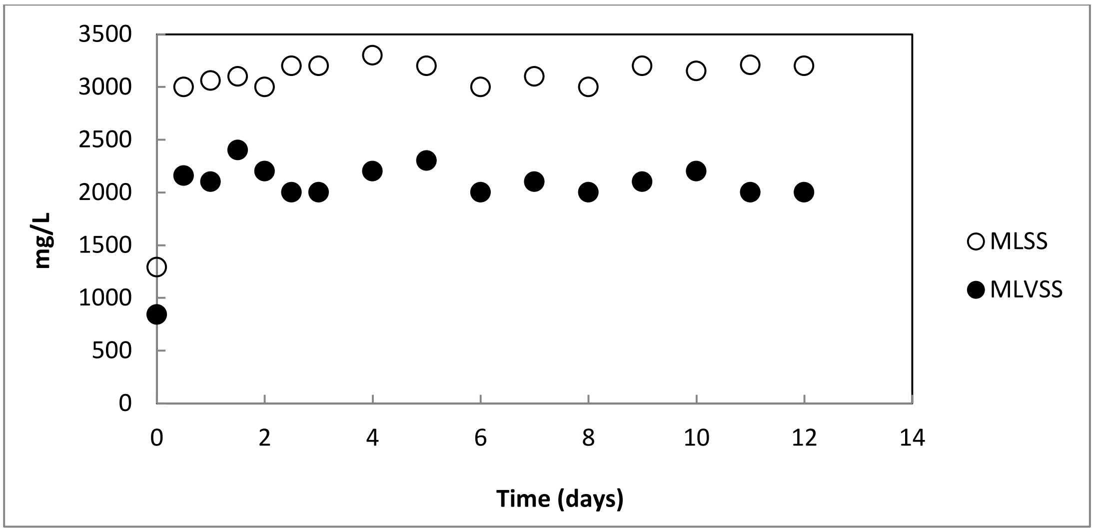

Figure 4.15 : MLSS and MLVSS profiles operated under acetate of 1000 mg COD/L and SRT = 1.0 d.

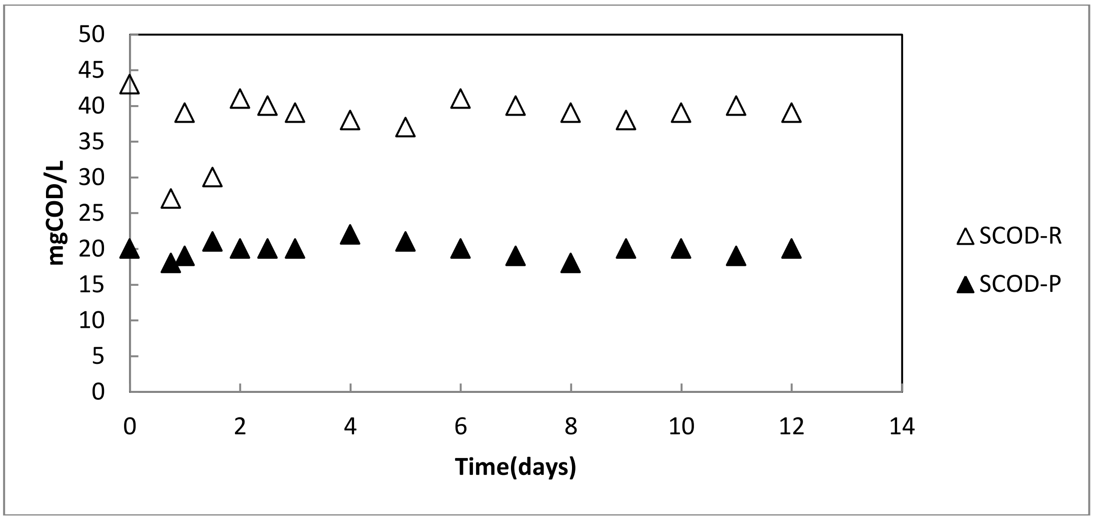

Figure 4.16 : Soluble reactor and permeate COD operated under acetate of 1000 mg COD/L and SRT = 1.0 d.

As seen from Figure 4.15, the steady state MLVSS was around 2000 mg MLVSS/L where as SCOD-R and COD-P were 60 mg COD/L (94 % COD removal efficiency) and 21 mg COD/L (98 % COD removal efficiency), respectively.

Experimental studies aiming to determine the performance of MBR operated with low SRTs (SRT = 0.5 to 2.0 d), revealed that, the suggested MBR operation approach successifully yielded high quality effluents for both synthetic wastewater feeds, one of them being a substrate mixture representing readily biodegradable soluble COD fraction of domestic wastewater and the other one being a single substate solution, i.e. acetate. The monitored MLSS and MLVSS profiles shown that the ratio of MLVSS/MLSS increased with decreasing SRT, which indicated that a more active bacterial community could be established at low SRT operation. The soluble COD profiles monitored inside the bioreactors tended to be higher than the COD values observed in the effluent streams which was attributed to generation of SMPs during the biological processes as the influent COD was assumed to be totally biodegradable, which was supported with the finding that the SMP increased with the increasing SRT.

4.2.2 Evaluation of steady-state protein and carbohydrate concentrations in the reactor

The EPS and SMP level of the sludge are important parameters in evaluating the fouling propensity of the MBR sludge. The levels of proteins and carbohydrates are commonly associated with SMP and EPS. Hence the protein and carbohydrate measurements were conducted accordingly.

The proteins and carbohydrate samples associated with SMP and EPS were taken from the bioreactor at steady-state and were analysed as carbohydrate (SMP-C and EPS-C) and protein (SMP-P and EPS-P) . The Figure 4.17 and 4.18 show protein and carbohydrate levels associated with SMP and EPS obtained from different experimental runs employing different SRTs.

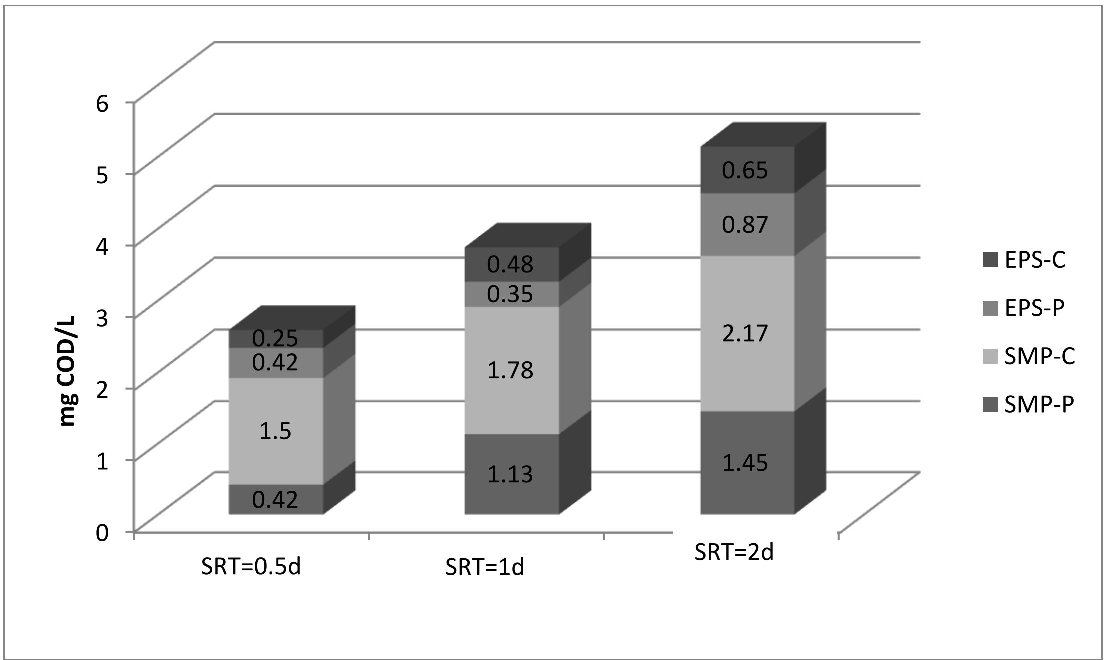

Figure 4.17 : The concentrations of SMP and EPS in sludge operated with initial COD of 200 mg/L.

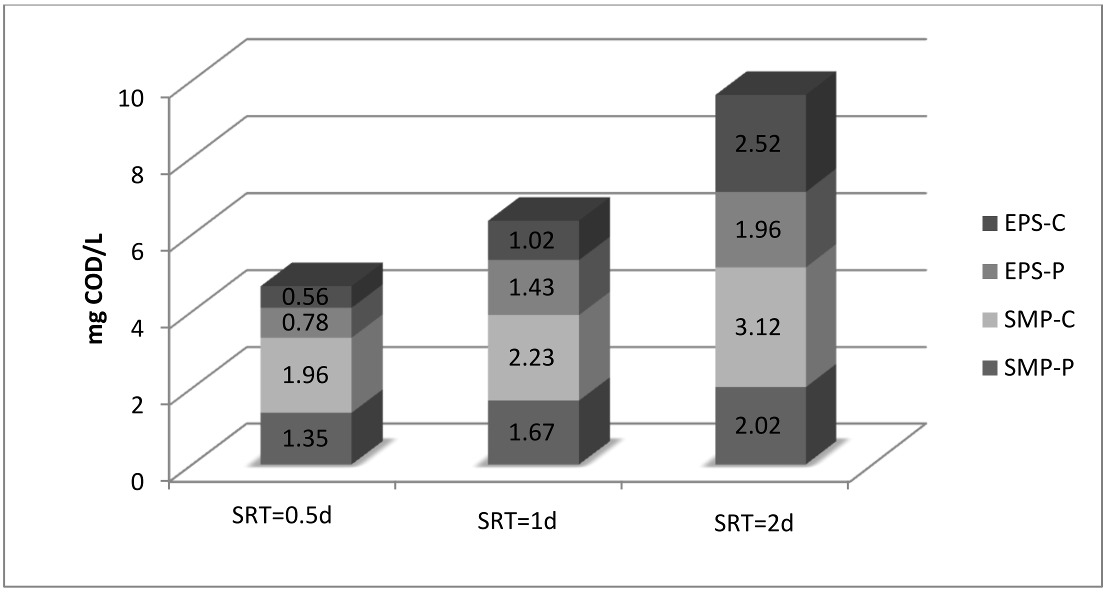

Figure 4.18 : The concentrations of SMP and EPS in sludge operated with initial COD of 1000 mg/L.

It was clearly shown that protein and carbohydrate levels associated with SMP and EPS content of MBR sludge produced at low SRT between 0.5 - 2.0 d are lower than systems operated with high SRT. It was also shown that protein and carbohydrate levels associated with SMP was higher than the protein and carbohydrate levels associated with EPS for all experimental runs. The effect of substrate concentration on EPS and SMP associated protein and carbohydrate levels was observed in sMBR as well, where both EPS and SMP associated protein and carbohydrate concentrations were increased with increasing substrate concentration.

4.3 Evaluation of Respirometric Studies

The respirometric studies based on OUR evaluation approach often uses modelling and relies on the adoption of dissolve oxygen as a significant model component (Vanrolleghem, 1995). Changes in the OUR profile reflect significant stoichiometric and kinetic information on biodegredation process. The OUR profile starts with endogenous respiration level, increases as a function of the observed removal rate after substrate addition and goes down to the initial endogenous respiration level after all available subtrate is depleted.

In the related study after assuring the steady-state conditions in the sMBR with both readily biodegradible mixture and acetate, respirometric measurements and COD monitoring were performed to determine the microbial oxygen utilization rate while the F/M ratio was kept the same as the reactor. The OUR profile and soluble COD profile during the OUR test are demonstrated in Figures (4.19- 4.34) below.

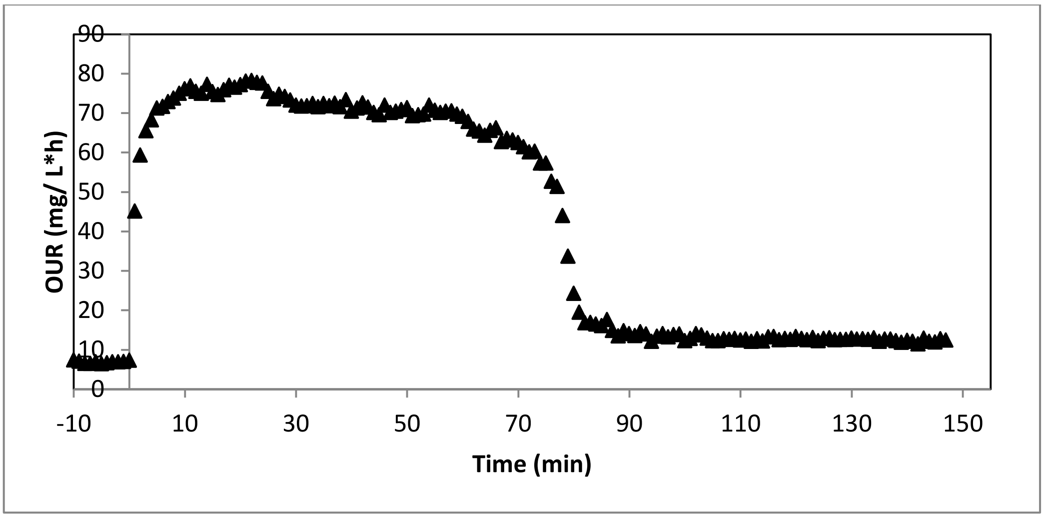

Figure 4.19 : MBR respirometer result (readily biodegradable substrate of 200 mg COD/L and SRT = 2.0 d).

As seen from the Figure 4.19, after addition to the substrate into the chamber, OUR values in the profile dropped to the initial endogenous respiration level within a period lower than the HRT implemented for the corresponding experiment. OUR profile indicates that total substrate was utilized in 80 minutes.

Figure 4.20 shows the soluble COD results obtained from OUR samples which have been analyzed from the samples taken at certain time intervals. As seen from the COD values presented in Figure 4.18, COD concentration was 35 mg/L in the endogenous level, increased to a maximum of 215 mg/L and was decreased to 40 mg/L in the final sample.

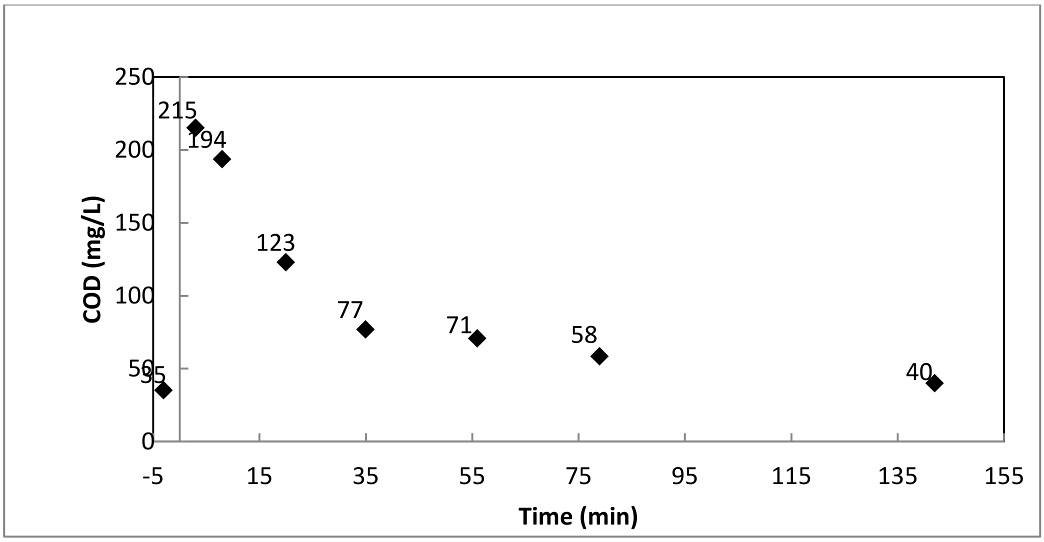

Figure 4.20 : MBR respirometer filtered COD result (readily biodegradable substrate of 200 mg COD/L and SRT = 2.0 d).

As seen from the Figure 4.21, after addition to the substrate in chamber OUR values in the profile dropped to the initial endogenous respiration level within a period lower than the HRT implemented for the corresponding experiment. OUR profile indicates that total substrate was utilizied in 60 minutes.

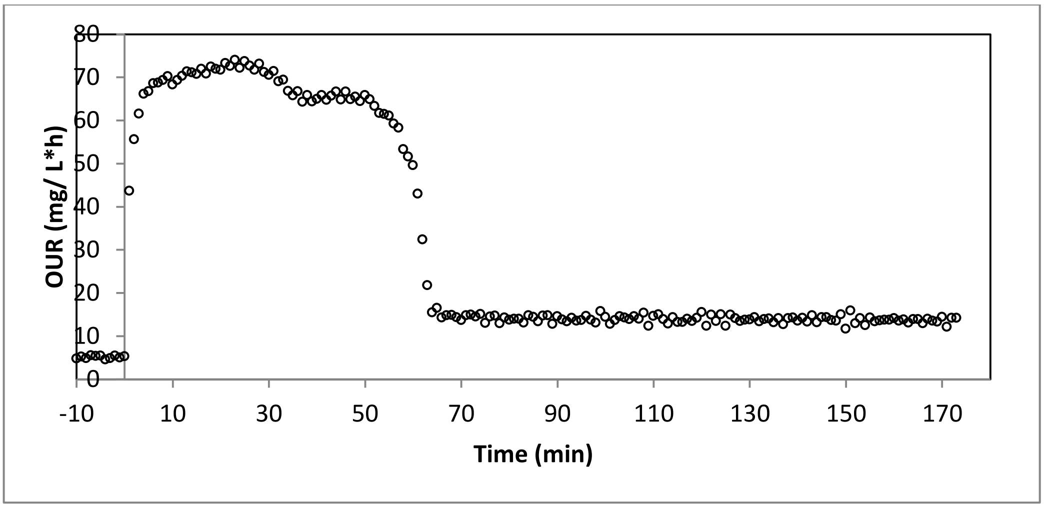

Figure 4.21 : MBR respirometer result (readily biodegradable substrate of 200 mg COD/L and SRT = 1.0 d).

Figure 4.22 shows the soluble COD results obtained from OUR samples which have been analyzed from the samples taken at certain time intervals. As seen from the COD values presented in Figure 4.20, COD concentration was 36 mg/L in the endogenous level, increased to a maximum of 215 mg/L and was decreased to 39 mg/L in the final sample.

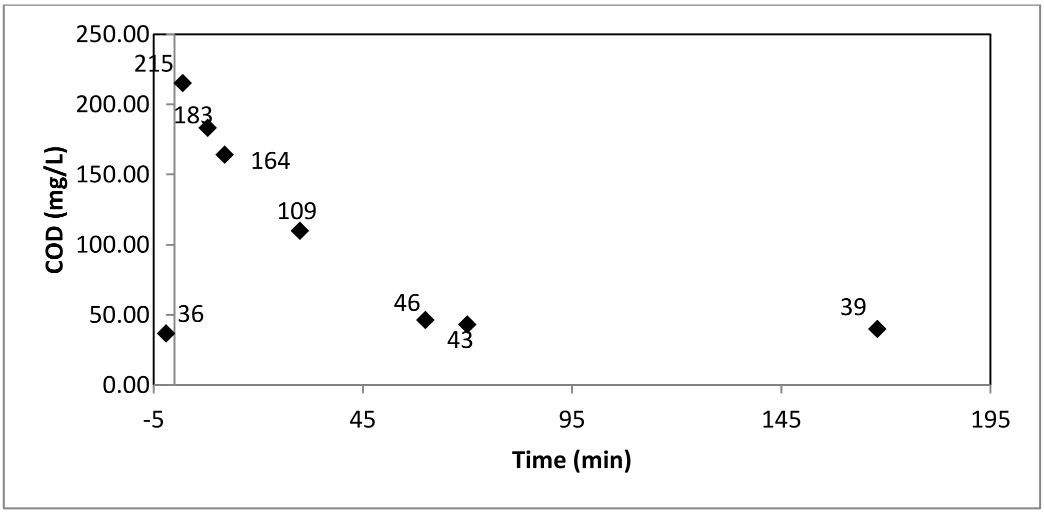

Figure 4.22 : MBR respirometer filtered COD result (readily biodegradable substrate of 200 mg COD/L and SRT = 1.0 d).

As seen from the Figure 4.23, after addition to the substrate in chamber OUR values in the profile dropped to the initial endogenous respiration level within a period lower than the HRT implemented for the corresponding experiment. OUR profile indicates that total substrate was utilizied in 60 minutes.

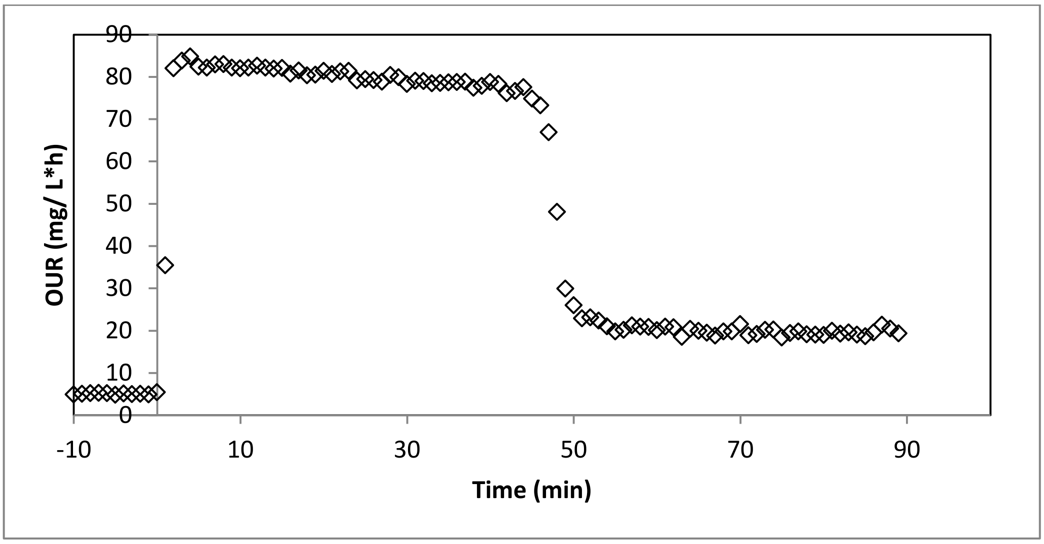

Figure 4.23 : MBR respirometer result (readily biodegradable substrate of 200 mg COD/L and SRT = 0.5 d).

Figure 4.24 shows the soluble COD results obtained from OUR samples which have been analyzed from the samples taken at certain time intervals. As seen from the COD values presented in Figure 4.24, COD concentration was 21 mg/L in the endogenous level, increased to a maximum of 247 mg/L and was decreased to 24 mg/L in the final sample.

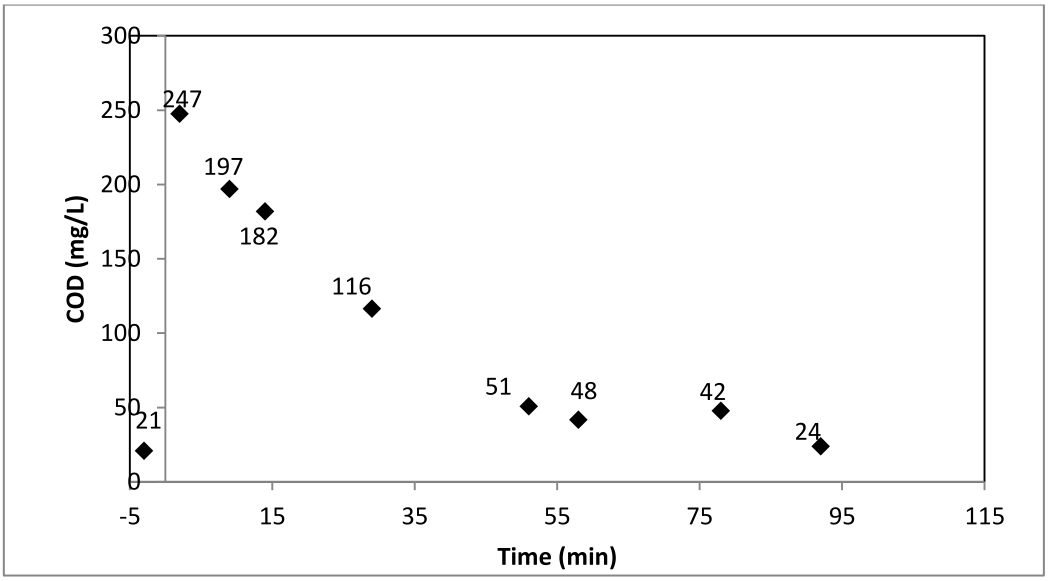

Figure 4.24 : MBR respirometer filtered COD result (readily biodegradable substrate of 200 mg COD/L and SRT = 0.5 d).

As seen from the Figure 4.25, after addition to the substrate in chamber OUR values in the profile dropped to the initial endogenous respiration level within a period lower than the HRT implemented for the corresponding experiment. OUR profile indicates that great part of the substrate was utilizied in 100 minutes.

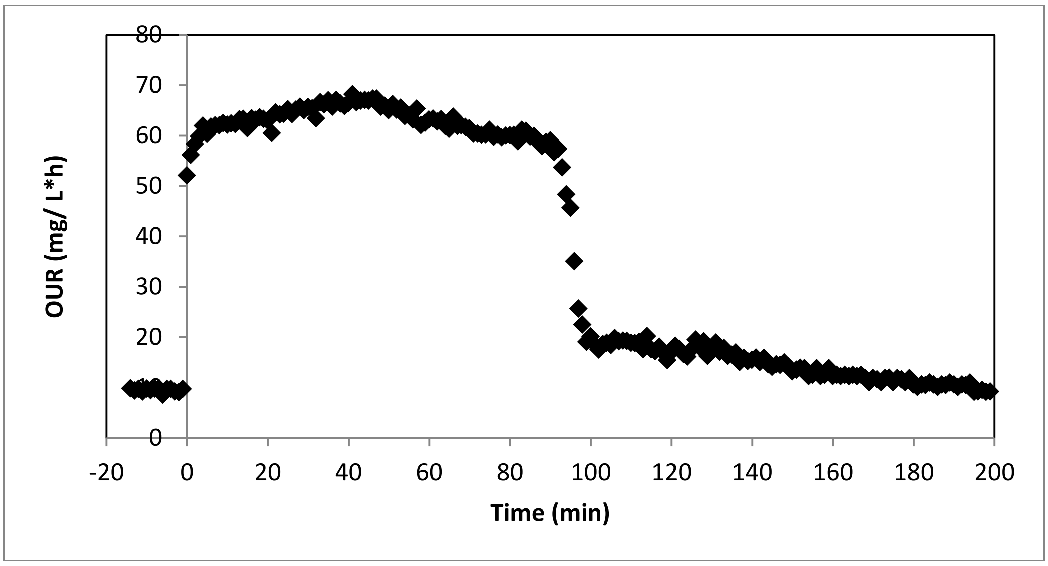

Figure 4.25 : MBR respirometer result (readily biodegradable substrate of 1000 mg COD/L and SRT = 2.0 d).

Figure 4.26 shows the soluble COD results obtained from OUR samples which have been analyzed from the samples taken at certain time intervals. As seen from the COD values presented in Figure 4.26, COD concentration was 28 mg/L in the endogenous level, increased to a maximum of 212 mg/L and was decreased to 31 mg/L in the final sample.

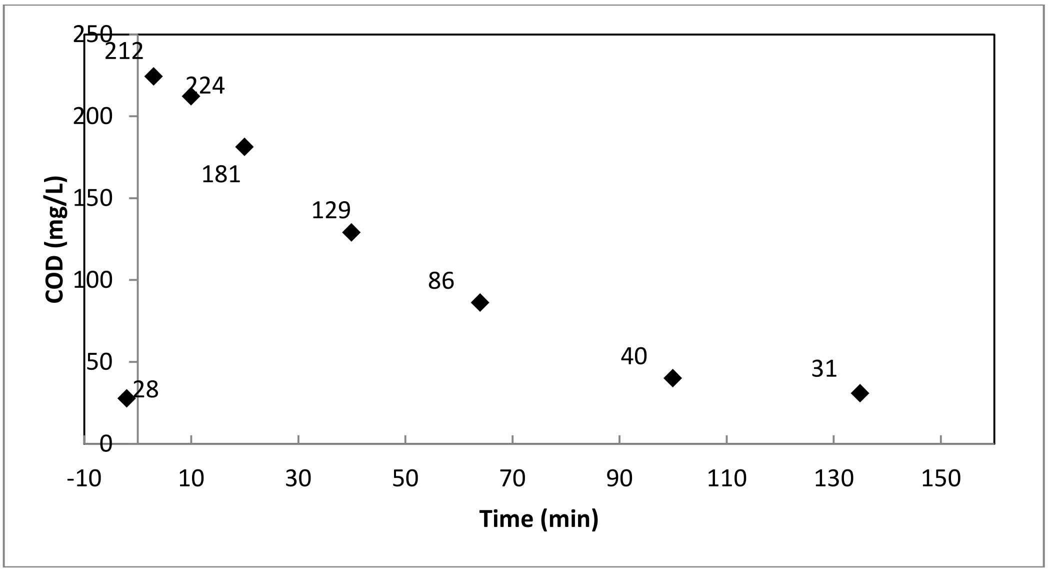

Figure 4.26 : MBR respirometer filtered COD result (readily biodegradable substrate of 1000 mg COD/L and SRT = 2.0 d).

As seen from the Figure 4.27, after addition to the substrate in chamber OUR values in the profile dropped to the initial endogenous respiration level within a period lower than the HRT implemented for the corresponding experiment. OUR profile indicates that great part of the substrate was utilizied in 110 minutes.

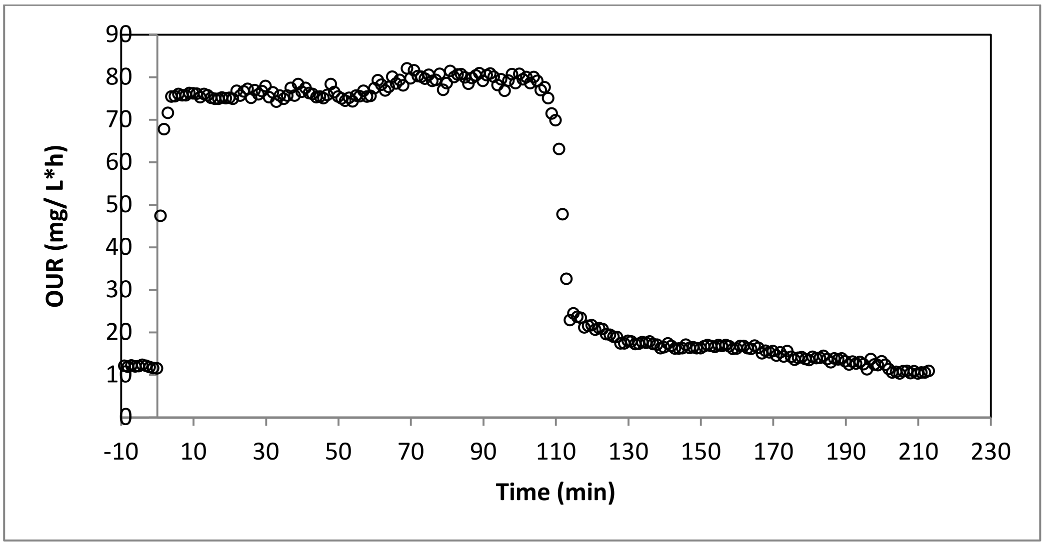

Figure 4.27 : MBR respirometer result (readily biodegradable substrate of 1000 mg COD/L and SRT = 1.0 d).

Figure 4.28 shows the soluble COD results obtained from OUR samples which have been analyzed from the samples taken at certain time intervals. As seen from the COD values presented in Figure 4.28, COD concentration was 54 mg/L in the endogenous level, increased to a maximum of 401 mg/L and was decreased to 56 mg/L in the final sample.

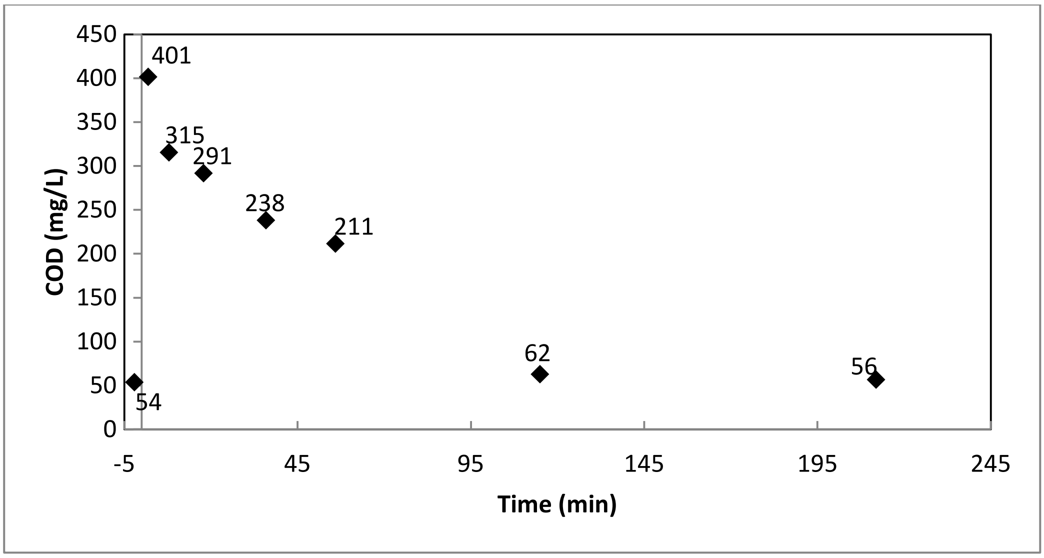

Figure 4.28 : MBR respirometer filtered COD result (readily biodegradable substrate of 1000 mg COD/L and SRT = 1.0 d).

As seen from the Figure 4.29, after addition to the substrate in chamber OUR values in the profile dropped to the initial endogenous respiration level within a period lower than the HRT implemented for the corresponding experiment. OUR profile indicates that great part of the substrate was utilizied in 120 minutes.

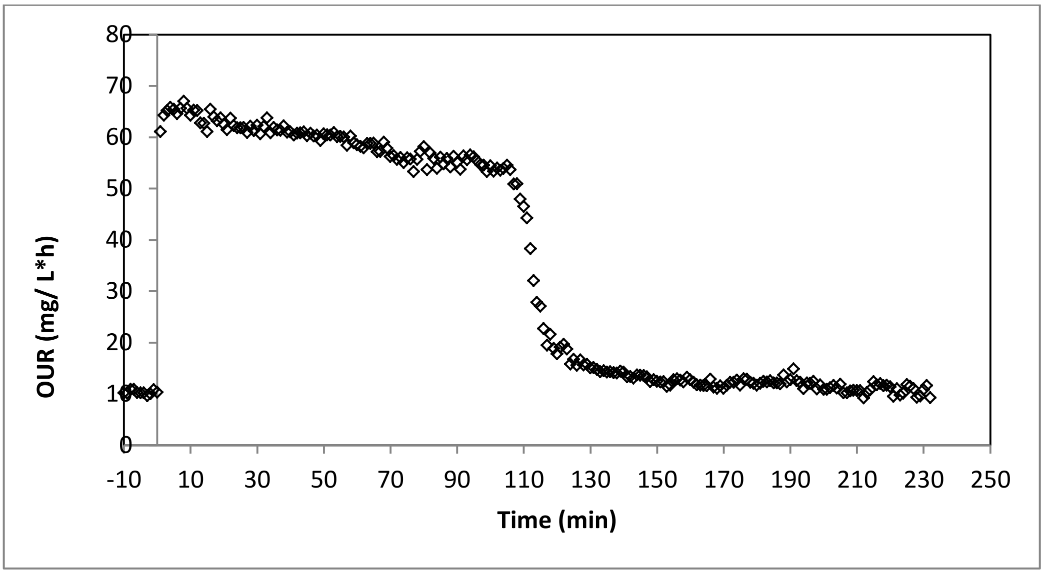

Figure 4.29 : MBR respirometer result (readily biodegradable substrate of 1000 mg COD/L and SRT = 0.5 d)

Figure 4.30 shows the soluble COD results obtained from OUR samples which have been analyzed from the samples taken at certain time intervals. As seen from the COD values presented in Figure 4.30, COD concentration was 6 mg/L in the endogenous level, increased to a maximum of 214 mg/L and was decreased to 9 mg/L in the final sample.

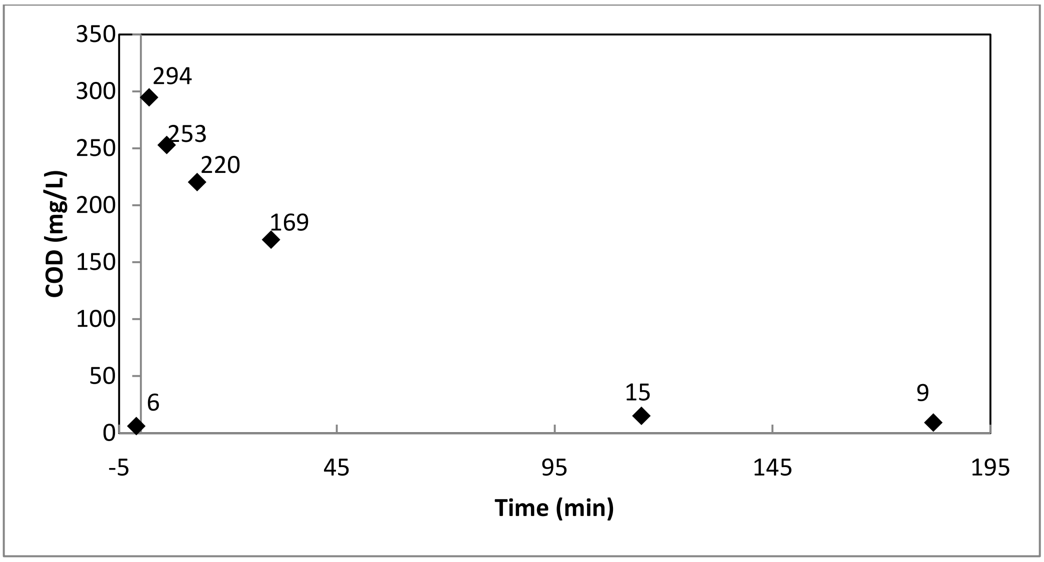

Figure 4.30 : MBR respirometer filtered COD result (readily biodegradable substrate of 1000 mg COD/L and SRT = 0.5 d).

As seen from the Figure 4.31, after addition to the substrate in chamber, OUR values in the profile dropped to the initial endogenous respiration level within a period lower than the HRT implemented for the corresponding experiment. OUR profile indicates that great part of the substrate was utilizied in 80 minutes.

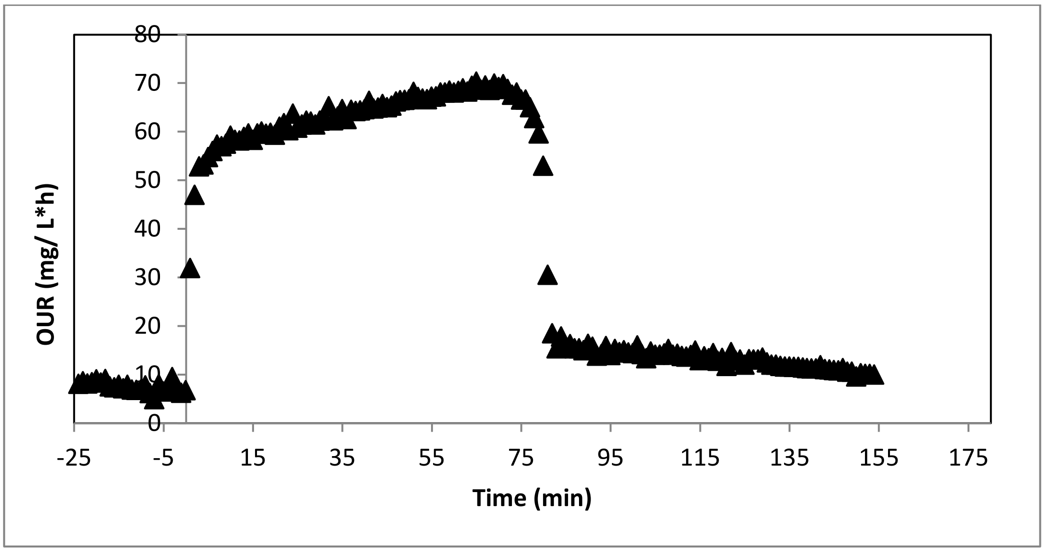

Figure 4.31 : MBR respirometer result (Acetate of 200 mg COD/L and SRT = 1.0 d).

Figure 4.32 shows the soluble COD results obtained from OUR samples which have been analyzed from the samples taken at certain time intervals. As seen from the COD values presented in Figure 4.32, COD concentration was 37 mg/L in the endogenous level, increased to a maximum of 208 mg/L and was decreased to 45 mg/L in the final sample.

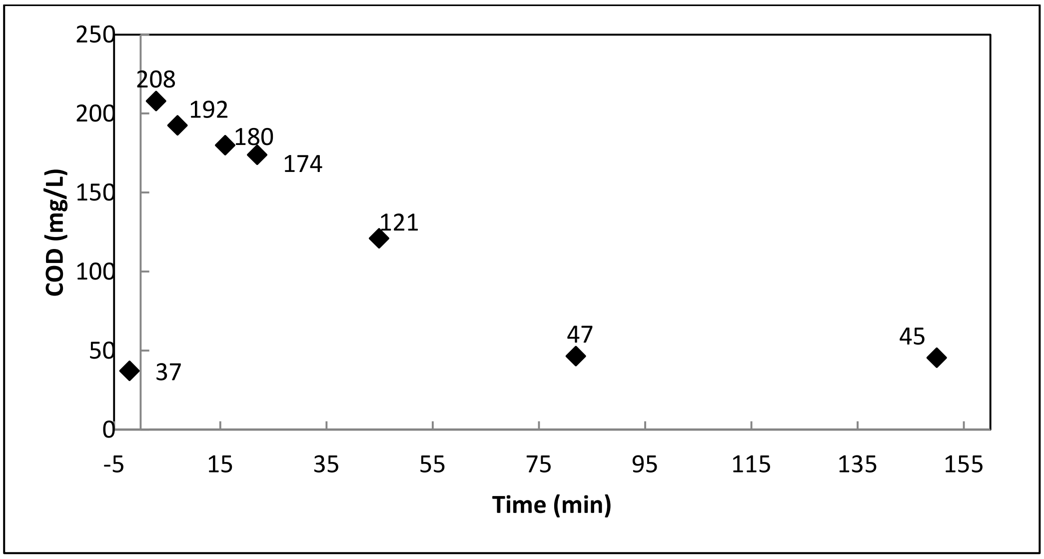

Figure 4.32 : MBR respirometer filtered COD result (Acetate of 200 mg COD/L and SRT = 1.0 d).

As seen from the Figure 4.33, after addition to the substrate in chamber, OUR values in the profile dropped to the initial endogenous respiration level within a period lower than the HRT implemented for the corresponding experiment. OUR profile indicates that great part of the substrate was utilizied in 50 minutes.

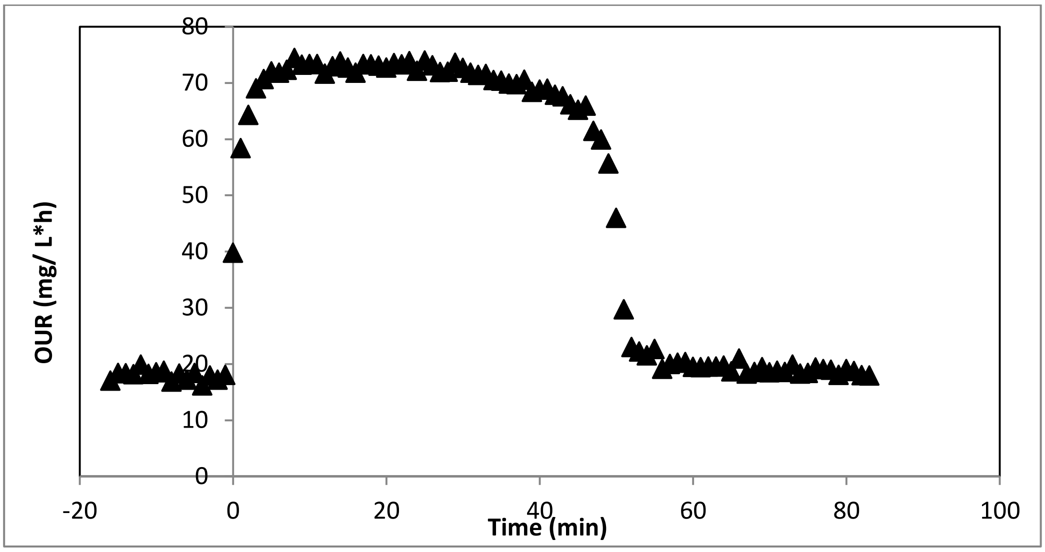

Figure 4.33 : MBR respirometer result (Acetate of 1000 mg COD/L and SRT = 1.0 d).

Figure 4.34 shows the soluble COD results obtained from OUR samples which have been analyzed from the samples taken at certain time intervals. As seen from the COD values presented in Figure 4.34, COD concentration was 19 mg/L in the endogenous level, increased to a maximum of 122 mg/L and was decreased to 22 mg/L in the final sample.

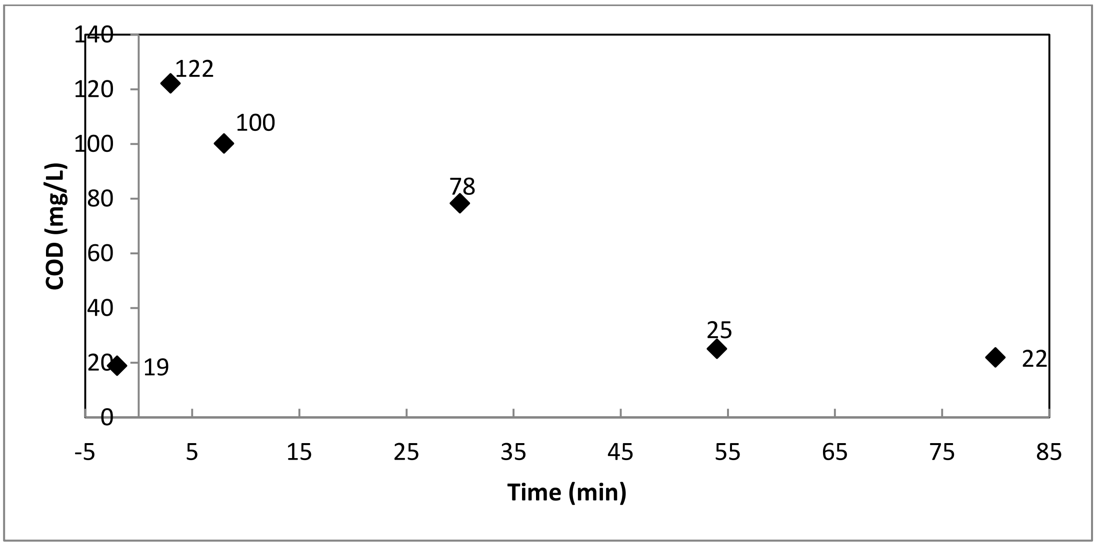

Figure 4.34 : MBR respirometer filtered COD result (Acetate of 1000 mg COD/L and SRT = 1.0 d).

Figure 4.34 shows the soluble COD results obtained from OUR samples which have been analyzed from the samples taken at certain time intervals. As seen from the COD values presented in Figure 4.34, COD concentration was 19 mg/L in the endogenous level, increased to a maximum of 122 mg/L and was decreased to 22 mg/L in the final sample.

The results of the parallel batch respirometric results can be best evaluated by distinguishing between the experiments conducted with synthetic substrate mixture representing readily soluble COD in wastewater of 200 mg COD/L and 1000 mg COD/L, at SRT of 2.0, 1.0 and 0.5 d; and experiments conducted with acetate of 200 mg COD/L and 1000 mg COD/L, at SRT of only 1.0 d.

In the respirometric studies run with synthetic substrate mixture, for both feeds adjusted to 200 mg COD/L and 1000 mg COD/L, it was observed that the COD introduced at the beginning of the test was reduced to its endogenous phase for all experimental runs and all at a considerably shorter time period than the employed HRT of 8 h. It was also observed that the time required to reduce the soluble COD in the batch reactor to its level at the endogeneous phase was decreased as the SRT was decreased. This was attributed to the dominance of active biomass in the case of operation at low SRT, compared to the relatively inactive biomass observed in reactors when long SRTs are employed.

In the respiromentric studies run with acetate, for both feeds adjusted to 200 mg COD/L and 1000 mg COD/L, it was again observed that all the COD introduced beginning of the test was reduced to its endogenous phase. As expected, the time required to reduce the soluble COD in the batch reactor to its level at the endogeneous phase was decreased as the initial COD was decreased.

4.4 Evaluation of Substrate Storage

Although it was known that carbon sources are used for growth and respiration processes, accumulation of internal storage polymers was observed in a number of studies (Zevenhuisen and Ebbnik, 1974; Van den Eynde et al., 1984)

The PHA samples were taken from the respirometer chamber against time and were analyzed. The Figures (4.35- 4.38) show PHB, PHV and PHA concentration profiles obtained from parallel batch respirometric experimental tests employing different SRTs and different substate feeds.

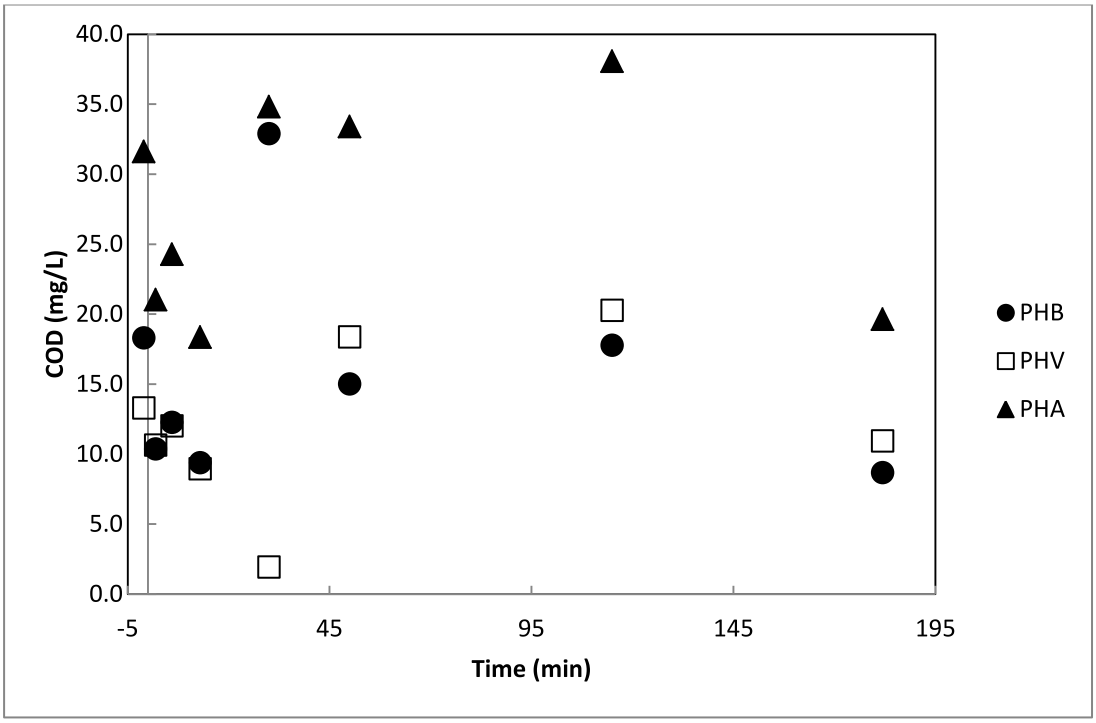

Figure 4.35 : The concentrations of PHB-PHV-PHA in sludge operated at SRT=0.5 d and 1000 mg/L COD, Readily Biodegradible Mix Substrate.

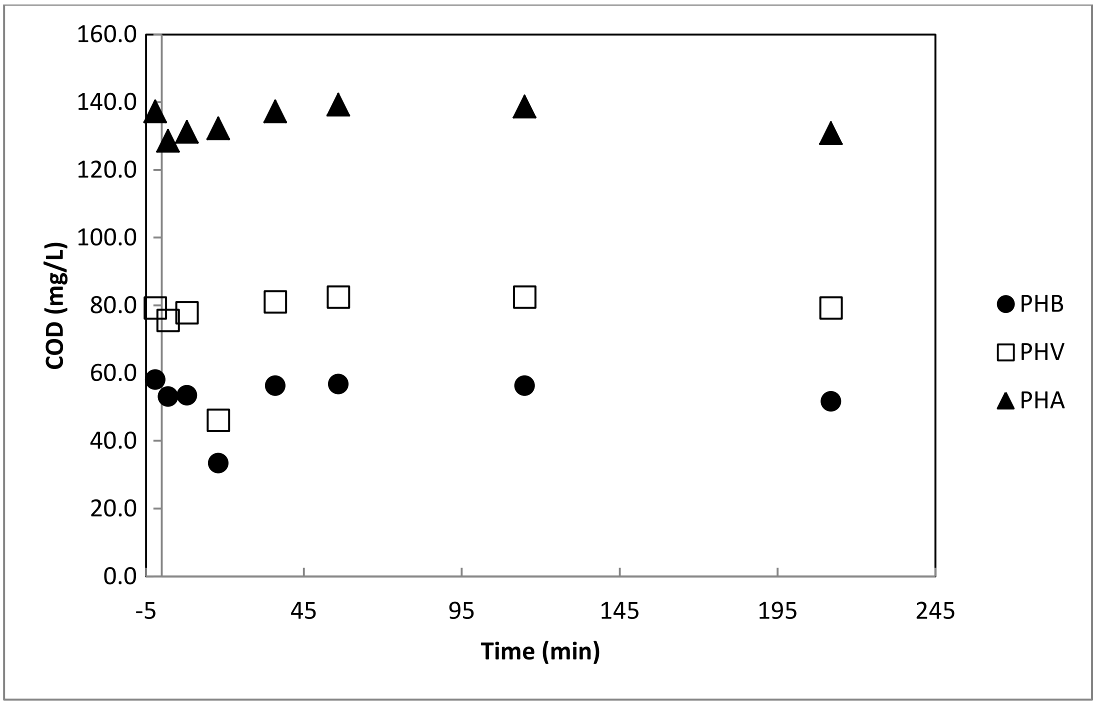

Figure 4.36 : Figure 0.36 :The concentrations of PHB-PHV-PHA in sludge operated at SRT=1.0 d and 1000 mg/L COD, Readily Biodegradible Mix Substrate.

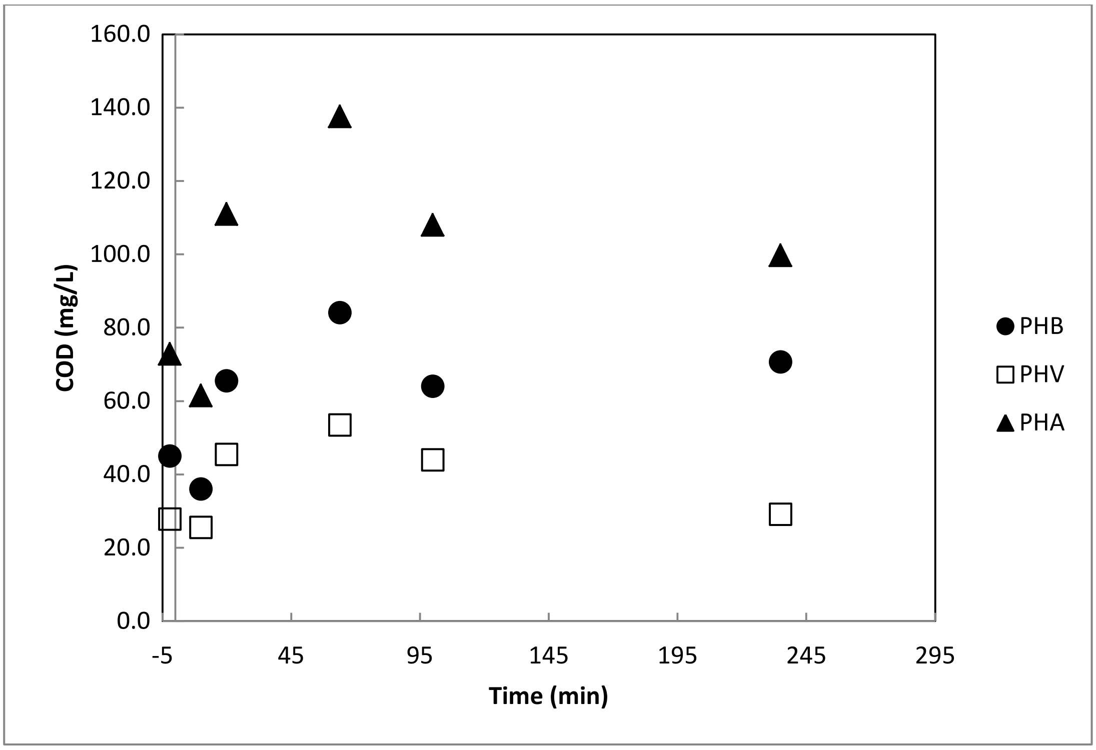

Figure 4.37 : The concentrations of PHB-PHV-PHA in sludge operated at SRT=2.0 d and 1000 mg/L COD, Readily Biodegradible Mix Substrate.

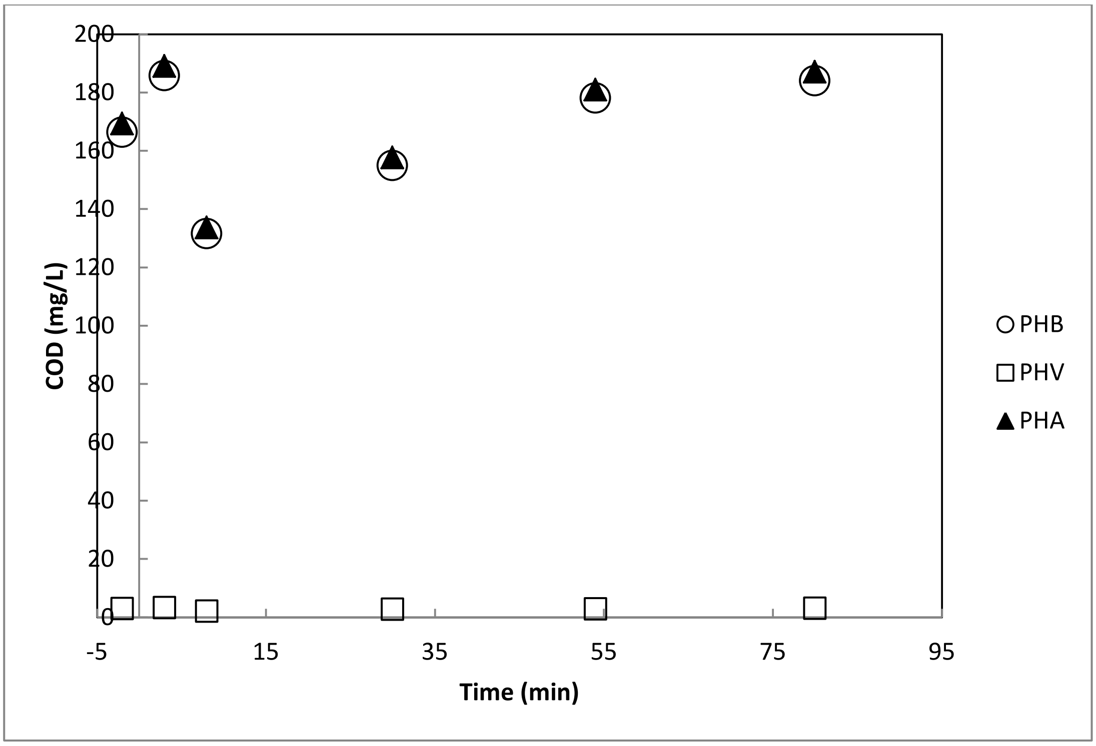

Figure 4.38 : The concentrations of PHB-PHV-PHA in sludge operated at SRT=1.0 d and 1000 mg/L COD, Acetate.

Analysis of storage polymers, namely, PHA, PHB and PHV have shown significant difference between the two synthetic feeds. As seen from the Figures (4.35- 4.37), in all experimental tests which were conducted with readily biodegradible mix substrate, all three polymers could be detected. Results were compatible with the literature. It is reported that when activated sludge culture is fed with volatile fatty acids (VFAs) the storage polymers are PHAs and if the system is fed with only acetate the PHA formed is mostly poly-β-hydroxy butyrate (PHB). When activated sludge is fed with glucose the storage polymer is reported as glycogen (Majone et al., 1999). In Figure 4.38, it can be seen that there was no PHV storage and the levels of PHA and PHB storage were almost equal.

4.5 Evaluation of Sludge Dewaterability

The samples were taken from wasted sludge and were analyzed. Table 4.3 shows the experimental results of sMBR sludge dewaterability properties obtained from different experimental runs employing different SRTs and synthetic substrate feeds having COD concentrations of 200 and 1000 mg/L.

Table 4.2 : CST results obtained from sMBR sludge.

	Readily Biodegradible Substrate Mixture						**Acetate**	
Concentration (mg COD/L)	200			1000			200	1000
SRT (d)	2	1	0.5	2	1	0.5	1	1
CST (sec)	35.6	28.1	15.85	50.3	31.5	20.9	32.3	45.5

CST results show that when the SRT was increased, the sludge dewaterability properties deteriorated. These experimental results were compatible with the protein and carbohydrate measurements, which also indicated that protein and carbohydrate concentrations associated with the fouling species, EPS and SMP, increased with increasing SRT.

Table 4.3 : Summary of Results.

	Readily Biodegradible Substrate						Acetate	
	Substrate 200 mg COD/L			Substrate 1000 mg COD/L			Substrate 200 mg COD/L	Substrate 1000 mg COD /L
	SRT=2 d	SRT=1 d	SRT=0.5 d	SRT=2 d	SRT=1 d	SRT=0.5 d	SRT=1 d	SRT=1 d
MLVSS (mg /L)	450	350	280	2400	1740	1135	400	2000
SCOD-R (mg /L)	37	36	23	100	65	59	39	60
COD-P (mg /L)	20	10	15	56	45	50	20	21
COD removal efficiency (%)	90	95	93	94	96	95	90	98
EPS-C (mg COD/L)	0.65	0.48	0.25	2.52	1.02	0.56	0.52	1.12
EPS-P (mg COD/L)	0.87	0.35	0.42	1.96	1.43	0.78	0.21	1.31
SMP-C (mg COD/L)	2.17	1.78	1.5	3.12	2.23	1.96	1.53	2.18
SMP-P (mg COD/L)	1.45	1.13	0.42	2.02	1.67	1.35	1.09	1.54
CST (sec)	35.6	28.1	15.85	50.3	31.5	20.9	32.3	45.5

5. CONCLUSION AND RECOMMENDATIONS

MBR systems are increasingly popular in domestic and industrial wastewater treatment since they offer several operational advantages over conventional activated sludge systems such as better control of operational parameters and superior effluent quality. Enforcement of municipal and industrial wastewater discharge standards and increasing number of recycle/reuse applications have resulted in preference of MBR system applications.

The general approach in MBR applications is to operate these systems at longer sludge retention times (SRT) in order to have higher biomass concentrations in the bioreactor, to allow slowly-growing microorganism to grow in the system and to reduce the volume of sludge to be handled. In this respect, MBR systems have been mimicking conventional activated sludge systems with no particular innovation offered in terms of operational approaches towards much efficient material and energy use. Although the reduced amount of biomass production obtained at higher SRT, as deemed advantageous in MBR applications, may seem advantageous in terms of system operation and sludge handling, the new approaches in energy, especially the policies targeting self-sufficient treatment plants, are stating that the biomass is actually a valuable alternative fuel in terms of energy production.

The purpose of this study is to investigate the performance of submerged MBR system operated at extremely low SRT in removing only the readily biodegradable/soluble COD from wastewater while the larger organics/particulates are retained by the membrane and/or adsorbed onto microbial flocs. In this respect, a laboratory scale submerged MBR was operated at three different SRT of 2.0, 1.0 and 0.5 days. For each level of the selected sludge age, hydraulic retention time (HRT) of the system was adjusted to 8 hours. Two different synthetic substrate feedings were tested; (a) soluble/readily biodegradable substrate mixture and (b) acetate. The synthetic mixture representing readily biodegradable COD in wastewater was tested at all SRTs, whereas synthetic feed constituting only acetate was tested only at SRT of 1.0 day. The synthetic feeds were adjusted to first 200 mg COD/L and than 1000 mg COD/L for the experimental runs.

The experimental works covered monitoring of carbon removal performance of suggested MBR operation scheme supported with respirometric tests and sludge properties.

Operation of the submerged MBR at selected operational conditions have shown that, high quality effluents could be achieved even at very low SRT, i.e. SRT = 0.5 – 2.0 days, where the COD removal performance was above 90 % under all conditions. In the case where synthetic substrate mixture representing the readily biodegradable soluble portion of the wastewater was used having 200 mg COD/L and 1000 mg COD/L; the effluent COD remained below 18 mg COD/L and 56 mg COD/L, respectively. Likewise for the synthetic substrate only constituting acetate having 200 mg COD/L and 1000 mg COD/L; the effluent COD remained below 20 mg COD/L and 29 mg COD/L, respectively. The soluble COD profiles monitored inside the bioreactors tended to be higher than the COD values observed in the effluent streams which was attributed to generation of SMPs during the biological processes as the influent COD was assumed to be totally biodegradable, which was supported with the finding that the SMP increased with the increasing SRT. The levels of proteins and carbohydrates were also measured in the reactor bulk liquid. The levels of these compounds, which are commonly associated with SMPs, were measured in the range of 2.59 – 9.62 mg COD/L, which constitute only a small fraction of the residual COD entrapped in the MBR.

The respirometric studies run with synthetic substrate mixture, for both feeds adjusted to 200 mg COD/L and 1000 mg COD/L, have shown that the COD introduced at the beginning of the test was reduced to its endogenous phase for all experimental runs. It was also observed that the time required to reduce the soluble COD in the batch reactor to its level at the endogeneous phase was decreased as the SRT was decreased. This was attributed to the dominance of active biomass in the case of operation at low SRT, compared to the relatively inactive biomass observed in reactors when long SRTs are employed. In the respirometric studies run with acetate, for both feeds adjusted to 200 mg COD/L and 1000 mg COD/L, it was again observed that all the COD introduced beginning of the test was reduced to its endogenous phase. As expected, the time required to reduce the soluble COD in the batch reactor to its level at the endogeneous phase was decreased as the initial COD was decreased.

Storage polymers were investigated in the samples taken from parallel batch tests, where the synthetic feeds were adjusted to 1000 mg COD/L. Analysis of storage polymers, namely, poly hydroxyl alkanoate (PHA), poly-b-hydroxybutyrate (PHB) and poly hydroxyvalerate (PHV) have shown significant difference between the two synthetic feeds. For the synthetic feed constituting only acetate, the results indicated that there was no PHV storage and the levels of PHA and PHB storage were almost equal. In the case where the readily biodegradable substrate mixture was tested, all three polymers could be detected. The results were consistent with the literature findings.

In order to support the potential use of sludge generated in the suggested MBR operation approach, as an alternative fuel and to have data on its fouling propensity, it is important to determine the dewaterability of the sludge. The sludge samples obtained from all experimental runs were analyzed for their Capillary Suction Time (CST) values. The CST analysis indicated that, for both synthetic substrates tested, when the SRT was increased, the sludge dewaterability properties deteriorated. These experimental results were compatible with the protein and carbohydrate measurements, which also indicated that protein and carbohydrate concentrations associated with the fouling species, EPS and SMP, increased with increasing SRT.

Future research should be directed to several other aspects of MBR operation at low SRT, including modelling of activated sludge behavior and understanding of fouling under such operational conditions. Modelling studies would help developing a better understanding on microbial behavior and kinetics including generation of SMP and storage polymers. Observing the performance of the suggested MBR operation with a coarser membrane, with pore size comparable to bacterial size of around 0.45 μm, would help suggesting alternative membranes to be used for this system for different wastewater types. This MBR operation approach should also be tested for much lower HRT, i.e. HRT of 0.5 to 2.0 h, in order to prove as a treatment alternative which also saves considerably from the required reactor volumes. This is an important aspect to demonstrate since other research studies conducted at ITU Environmental Engineering Department using the same MBR operation approach by using a side stream MBR, which was able to reach filtration fluxes corresponding to

HRT of down to 0.5 to 2.0 h, indicated that effluent COD (removal efficiency over 90 %) was almost independent of the HRT employed for the tested SRTs of 0.5 to 2.0 d. Future studies should also study the treatment performance with different wastewater streams, mainly focusing on industrial wastewaters to demonstrate the capability of this system to treat various wastewater types. It is also important that the treatment performance of this system is tested with real wastewater after employing pre-settling.

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